The Ignis Fatuus of Biogas

Small-scale anaerobic digesters ("biogas plants"):
a critical review of the pre-1970 literature

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PREFACE

In the last five years, anxiety about the price and availability of oil has generated intense interest in the small-scale anaerobic digester, which produces fuel (methane, biogas) and fertilizer (an inoffensive, nitrogen-rich residue) by microbial action on manure and other agricultural wastes. Attempts to utilize anaerobic digesters on farms have a long history, and before 1970 considerable research was done in France, Germany, and the USA, where rather different aims were pursued independently. Interest was aroused and dwindled according to economic conditions, and the focus of development then shifted to India, and from there spread to other developing countries, some of which had direct contacts with Europe.

This publication reviews the pre-1970 interests in bihugas (or biogas) plants. In chapter 1 the subject is introduced and quotations are given to illustrate the uncritical, romantic, almost mythical way the prospects and potentialities of small-scale digesters have often been assessed. In chapter 2 some other applications of anaerobic digestion are briefly reviewed. In chapter 3 the history of biogas on the farm is reviewed for all countries where there has been interest in this subject. The major types of digester designs that have been used and proposed are reviewed in 34 figures. In chapter 4, pre-1970 literature on parameters affecting gas production is reviewed, and in chapter 5 data on the fertilizer value of the output are discussed. Most of the designs and performance data are here published in English for the first time. In chapter 6 a brief indication is given of economic and socio-cultural factors that affect the feasibility of small-scale digesters. The bibliography contains about 375 references, of which roughly 275 are specifically on small-scale digesters.

It was decided that this review should only go as far as 1970, partly because later work has been reviewed elsewhere, partly to make the point that present-day discussions are often echoes of older, forgotten controversies; and apparently novel inventions are sometimes really re-inventions.

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Centre for Appropriate Technology, both of this University. The revision was carried out while I was on leave at the Department of Chemical Engineering of the University of New Brunswick.

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Fredericton, N. B.
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INTRODUCTION

1.1 Early history of methane gas produced by fermentation[†]

One of the earliest to mention the mysterious appearance of flickering lights and flames emerging from below the surface of the earth, was Plinius. The explanation for this phenomenon was related to mythical classification systems: for example, the enormous pillar of fire, lasting eight days, that appeared in 4 A.D., at the Roode Klif, near Stavoren (Netherlands) was reported to be the activity of a local dragon.

By 1630 a more recognizable "scientific" taxonomy to examine the phenomenon of inflammable gases was developed by van Helmont. He listed among fifteen different kinds of gases, an inflammable gas that evolves during putrefaction and is also contained in intestinal gases. Shirley is sometimes quoted as having "discovered" marsh gas in 1667. However, it seems more appropirate to start the scientific history of methane digestion with Volta for the following reasons: from a number of observations, he concluded in 1776 that:

(a) the amount of gas that evolves is a function of the amount of decaying vegetation in the sediments from which the gas emerges;

(b) certain proportions of the gas so obtained forms an explosive mixture with air.

Volta also gave the first eudiometric analysis of methane; Cruikshank proved beyond doubt that methane does not contain oxygen (in 1801); and in 1804, Dalton gave the correct chemical formula for methane. In 1806, Henry confirmed that town gas was very similar to Volta's marsh gas.

The starting point of the history of anaerobic digestion applied to agricultural waste might be fixed in 1808, when Davy collected 0.3 liters methane (and twice as much carbon dioxide) from cattle manure kept in a retort under vaccuum.

Systematic investigations of anaerobic digestion started in the second half of the nineteenth century. Bunsen (1856) and in particular Hoppe-Seyler

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[†] This section is based on (A3, B13, C27). Combinations of one capital letter and a number, placed between round brackets, such as (A3) or (A3, B13, C27) refer to the bibliography.

(1886), made important contributions to the first microbiological knowledge of anaerobic digestion. With the work of Omelianskii (about 1900) and others, there was already considerable information on the process, by the time Söhngen wrote his thesis on the subject in 1906 (A3). It was understood that part or all of the organic materials were hydrolysed by what we now call enzymes and broken down into alcohols and fatty acids, whereas methane was formed from these products. Detailed investigations and discussions were carried out to assess the various intermediate products, in particular the role of hydrogen (which sometimes evolves as a gas, but usually is consumed at once), as well as to identify the bacteria responsible for anaerobic digestion.

In 1884, Louis Pasteur presented the results of his pupil Gayon at the Academy of Sciences in Paris. Gayon had fermented manure at 35°C, obtaining as much as 100 liters methane per cubic meter of manure. Pasteur concluded in his lecture that this fermentation process could be a source of heating and lighting, thus promoting a humoristic article in "Le Figaro" of March 5, 1884 (F1), and a request of the "Compagnie des Omnibus" in Paris to Gayon to design an installation in which the manure of their many horses could be digested to methane to be used for street lighting. However, Gayon refused, saying that his investigations were preliminary. Consequently, the general public had soon forgotten about this novel source of energy (F6).

At about the same time (1875), the Dutch farmer Wouter Sluys became the first to use methane for purposes of illumination. The gas was not generated by fermentation, but was natural gas from a well. By 1899, natural gas was used for lighting, and occasionally heating and cooking, on about 60 farms in The Netherlands (A1). After that, the number decreased as no new sources of natural gas were found.

From 1860 onwards, the idea of a septic tank was introduced in sewage purification (B1). Although it was known that methane was formed in these tanks and occasionally some of this was collected for research purposes, it was only in 1895 that Cameron in England designed a septic tank in which he could collect the gas produced. This gas was used for some time to light part of the streets of Exeter.

In 1897, a methane digester was installed at the Matinga Leper Asylum in Bombay to treat their wastes (E4). The methane was collected and used for lighting (and in 1907, also to drive a motor). From then on the possibility of using anaerobic digestion to treat wastes and to gain methane, has been considered repeatedly and in many countries. It has been applied for brief periods in various places, but apart from limited use at sewage works, it has never been really successful.

The historical development from 1900 onwards will be reviewed at appropriate places in chapters 2 and 3.

1.2 Characteristics of methane fermentation

Good review articles on the anaerobic digestion of organic materials to methane and carbon dioxide appear regularly (A10-17). Here, only a few of the more important characteristics that are relevant to the design and operation of small-scale digesters are listed.

(a) Almost any natural organic material can be converted partially to methane.[†] In all probability, lignin cannot be digested (see section 4.4). Whether mineral oils can be converted is a point of dispute (A9). However, from the fact that a particular material *can* be digested, it does not follow that, in a particular instance, it *will* be digested; nor does anything follow as to the time it will take to digest a certain part of the feed. This triviality is often passed over in recent literature concerned with promoting the idea of bihugas plants.[††]

(b) Complex organic substrates are broken down in three stages: (i) hydrolysis (by exo-enzymes) giving soluble compounds like sugars, (ii) formation of volatile fatty acids by facultative anaerobic bacteria, in particular acetic acid (and to a lesser extent lower alcohols, carbon dioxide, ammonia and hydrogen, depending on the prevailing substrate and ecology), (iii) methanogenesis by strictly anaerobic bacteria. Optimal conditions are not necessarily the same for each step, nor for the different microbes that are involved in step (ii) or (iii). It has been speculated in the literature that some of the groups of bacteria involved are antagonistic or symbiotic. Because nothing definite is known on this, nor what the rate determining steps are, there are good reasons to support any one of the basic types of operation: (i) batch operation, (ii) continuous operation in plug-flow, (iii) continuous operation, ideally stirred. No

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[†] See the data in tables 2.1 and 2.2 in chapter 2 and tables 4.1-4.5 in chapter 4.

[††] The term "bihugas plant" is not commonly used. Common terms are "biogas plant" and "methane digester" to denote units (usually small-scale) to produce methane from organic waste (usually dung or manure) by anaerobic digestion. The term "bihugas", being short for "biological humus and gas" was introduced in Germany in 1951 (G11-13), to indicate that the purpose of the bihugas plant was to produce both methane gas and a good processed manure by anaerobic digestion of fresh manure and organic farm wastes. It will be shown in subsequent chapters that whenever bihugas plants might be feasible for small-scale application, the manure processing aspect is at least as important as the gas production feature.

matter what operation is chosen, anaerobic digestion is a conglomerate of extremely sensitive equilibria, which are difficult to reach and easily disturbed.

(c) Optimal conditions quoted in the literature usually refer to the methane forming step. The pH should be between 6 and 8 and the volatile acids concentration (i.e., the substrate concentration for the third step) should not be too high. This is further discussed in section 4.5 together with the role of other nutrients and inhibitors. The optimal temperature is quoted as 35°C (mesophilic bacteria) or 55°C (thermophilic bacteria). The effect of absolute temperature and temperature variations is further discussed in section 4.3.

(d) To take advantage of the process, one needs bacteria to do the work. Anaerobic bacteria use only about ten per cent of the substrate for reproduction. This is an advantage if one is interested in methane and one has already a large culture. In actual practice, a major problem is therefore to acquire enough inoculum for batch operations or (in the case of continuous operation) to keep the active biomass in the reactor.

1.3 First digression: aspects of the history of digesters on farms in developed countries.

The notion (already apparent in 1884) that the manure of the tram-horses could be used to light the streets of Paris has been referred to in section 1.1. There are reports (H13) that methane gas was produced on a farm in Italy in 1910. In 1930, in the U.S.A., Buswell wrote (L3):

> It is believed that the completion of some development work now in progress will make it possible for farms and ranches to install digestion tanks in which various crop residues may be converted in considerable amounts to a gaseous fuel of high heat value.

But few digesters were ever constructed in the U.S.A., although development work went on until 1936 (see section 3.5).

In France, interest in the subject was stimulated by Ducellier and Isman, who, apparently, were quite certain about the reliability of their "invention", about which they wrote in 1945 (F9):

> Au cours de celles-ci, nous avons été assez heureux pour mettre au point une méthode de fermentation de conception entièrement nouvelle, qui élimine complètement tout danger de stérilisation et qui nous a permis d'obtenir du méthane avec une certitude absolue, hiver comme été.....

Anaerobic digestion was at that time thought of as the ubiquitous solution to the world-wide squabble for the diminishing resources of petroleum. In a small book on anaerobic digesters published in France in 1952, Mignotte wrote (F34):

> Plaçons-nous maintenant au point de vue de l'intérêt national. On sait que les importations d'essence entraînent des sorties considérables de devises. Ne vaudrait-il pas mieux réserver le maximum de ces devises à des importations de produit irremplaçables et réduire les achats de carburant en développant le production de gaz de fumier? La consommation d'essence dans le monde est en progression. Malgré la prospection de nouveaux gisements, n'allons-nous pas vers une crise? Le développement de la production du gaz de fumier permettrait de pallier les inconvénients de cette pénurie.

At that time it was said that about 600 digesters were in operation in France, and many more were expected. In another book, also published in 1952, Lesage and Abiet wrote (F33):

> Avec le recul des deux dernières années, on peut sans grand risque prévoir une diffusion rapidement croissante de cette production en raison à la fois des avantages qu'elle offre aux habitants de la campagne et de l'intérêt manifeste que cette récuperation représente pour l'économie nationale. . . . .
> Pour ces diverses raisons, le moment semble donc venu de promouvoir une politique nationale du gaz de fumier.

However, after 1950, no significant number of digesters were installed, and it seems that today only one is still in operation. The developments in France are further discussed in section 3.1.

In 1951, Rosenberg gave an influential lecture to the British Society of Agricultural Engineers, in which he suggested that all tractors in England and Wales might be fuelled with digester gas derived from manure. Many publications ensued both in England and the Commonwealth. However, at most, only a few digesters were ever installed in England. One digester in Gloucestershire is referred to over and over again in the literature. The lucky owner is quoted in "The Farm Implement and Machinery Review" in 1954 saying (K11):

> To have a source of power on tap is very, very nice, especially when you realize it is costing nothing. I can't see anything but good in it, myself.

But then, he had not paid for the installation himself. The digester ceased operation after five months.

Rosenberg also reported (K4) that Waldemar Harnish at Heidelberg (Germany) has produced considerable quantities of power gas. He used a windmill to drive the agitator that destroys the scum cover, and he places the whole tank into a greenhouse type of building, using the sun's heat to keep the temperature up to the required 86 degrees F.

This idea has recently been re-invented all over the world.

During the period 1949-1953, about twenty digesters were installed on farms in Germany. They appeared to be uneconomical, if not technically unfeasible, although Schimrigk had noted in 1950 that (M1):

> Wegen der groszen volkswirtschaftlichen Bedeutung... ist dringend geboten solche Anlagen in groszen Umfange zu errichten und zu betreiben.

In addition to manure, it was speculated that other inputs for anaerobic digestion might be realistic: cornstalks in the U.S.A., flotsam on the rivers of South America, seaweed on the shores of Japan, turf in Russia and Ireland. With respect to the latter, it was stated in the "Times Review of Industry" in 1954 (K13):

> The peat would merely be pulverized, mixed with sludge, seaweed or some other suitable material, and allowed to ferment in digesters under scientific control. It is believed not to be impossible that Ireland could become self-sufficient in fuel by converting indigenous turf into methane gas, while the joint-product of the process, humus, would greatly enrich the soil.

By the end of the 1950s, the turmoil brought about by this will-o'-the-wisp was almost at an end in Europe. However, as late as 1960 Cibrian, in Spain, wrote (H33):

> Una fuente de energia que actualmente no se aprovecha en nuestro pais y que puede contribuir a mejorar el nivel de vida de la poblacion rural, es el gas que puede producir el estiercol a fermentar, antes de ser incorporado al terreno.

while Barth, wrote as late as 1964 in "Technik und Landwirtschaft" (G61)

> Seit fast 50 Jahren bewegt das Thema "Biogas" die Gemüter der Wissenschaftler. Viel stille Labor-Arbeit und viele praktische Versuche waren erforderlich, bis dasz wir heute am Ausgangspunkt einer Entwicklung stehen die bei sinnvoller Anwendung der Landwirtschaft wesentliche Vorteile bieten kann.

But by then, general interest in bihugas in the industrialized countries had disappeared. It has recently been revived during the most recent energy crisis and the renewed interest in "natural" or "ecological" systems. Since about 1975, marginal interests in establishing bihugas plants on farms have emerged in almost all developed countries, but it seems safe to say that up till now, bihugas plants have not proven to be economically feasible (Q8, 10, 19).

1.4 Second digression: aspects of the history of digesters on farms in developing countries.

Indigenous interest in developing countries, in the potentialities of bihugas first emerged in 1939 at the Indian Agricultural Research Institute (IARI). By 1950, a large number of people and institutes in India were involved. Since the later part of the fifties there has been continuous and considerable government support for various programs to introduce bihugas digesters amongst the farmers. In 1961, a study was reported by Vishnoi and Boze on the effect of educational exposures regarding the acceptance of cow dung gas plants by farmers. Among other things, it was noted that (N18):

> The Institute [IARI] has installed eight gas plants, as demonstration units, in the Intensive Cultivation Scheme villages and though they have been working satisfactorily for the past 6-7 years, no other farmers have come forward to have the gas plant installed in their houses even on 50:50 basis.

As far as is known, this is the only pre-1970 evaluatory study of the success of government policies in this area. One other publication of a collaborator of IARI exists on the problems of introducing biogas plants, Idnani, who wrote in 1964 (N30):

> The farmer confessed to having stopped the addition of dung but could give no reason for doing this. He agreed that the labour involved was not much and it would certainly not come in the way of his routine work in the field. When asked whether he would like the gas plant to be repaired, he was rather hesitant but made up his mind to say that he would rather not have it despite all advantages. One by one the other plants followed it until today only five gas plants have been left.....

Certainly the main cause of lack of success was not the technical feasibility of biogas production per se, because Desai reported already in 1951 that (N6):

> A few firms have put on the market, plants of various designs and sizes.....Some of these can be seen working in private bungalows in the suburbs of Bombay and are reported to be functioning satisfactorily.....

The developments in India also created some interest in other countries in South-East Asia. Occasionally criticism was heard that biogas plants were only accessible to the rich farmer (P71):

> Some firms have brought gas plants onto the market, but they are quite expensive and normally out of the reach of an ordinary cultivator.

However, the majority of publications displays an extreme form of optimism with reference to the potentialities of biogas, for example, Rao wrote in 1963 (N27):

> Hence, the entire cost of installation is recovered within a few months of operation, and the farmer enjoys a free and perennial supply of gas fuel and high-quality manure....... The significance of bio-gas potential transcends its utility as merely an economic device to solve our fuel and power problems in rural areas. It will help us to develop rural cottage-scale industries based on small mechanical and electrical power units making the best of our local resources.

Most digesters in India have been installed via the programmes of the Khadi and Village Industry Commission (KVIC). It seems that for 20 years the same designs have been used for installing biogas plants (Q18).

In 1959, a special institute was established: the Gobar Gas Research Institute in Uttar Pradesh. Few publications exist on the activities of this Institute (Q1).

In 1975, about 17,000 digesters had been installed in India. It has been said that at the most, 30% of this number was in actual operation. Other sources stated that of the 75,000 digesters installed in 1979, the number of idle plants was not more than 10 to 15 per cent. It is very difficult to obtain reliable information on this. Systematic evaluatory studies have been started only very recently (R6).

From about 1958 onwards, significant numbers of digesters have been installed on farms, villages or communes in China, South Korea and Taiwan (Q12). For the People's Republic of China it is particularly difficult to evaluate the success of development policies. The lack of information from Korea or Taiwan may be an indication that the results are not only positive. With respect to Taiwan it seems that significant numbers of digesters have only been installed on medium- and large-scale hog (pig) farms. Three years ago the Korean Government obtained financial support from the British Government to evaluate the prospects of biogas digesters. This evaluation is being carried out by the Tropical Products Institute in England.

At various times from 1960 onwards (and increasingly so from 1970 onwards), various individuals have tried to promote anaerobic digesters in rural areas in numerous tropical countries: Nepal, Pakistan, Bangladesh, Thailand, Malaysia, Indonesia, Papua New Guinea, The Philippines, Fiji Islands, Egypt, Uganda, Tanzania, Ethiopia, Zambia, Nigeria, Mexico, Brazil, and presumably many others. From about 1975 onwards, a number of these countries, in particular in South East Asia, have started to take notice on a government level, of the possibilities of anaerobic digestion (Q5, 6, 9, 12, 20-24).

Numerous national and international organizations have shown interest in the subject. The International Development Research Centre (IDRC, Canada) as well as the National Academy of Sciences (USA) have commissioned publications on the subject (Q17, 20, 24). Also IDRC has recently financed projects in Bangladesh, Thailand, Korea and The Philippines on the subject of anaerobic digestion. UNIDO has applied for UNDP funds to finance comparative studies. The FAO organized a conference (in 1975) on agricultural waste treatment in the tropics, where anaerobic digestion received much attention (Q13). The Economic and Social Commission for Asia and the Pacific (ESCAP) started in 1975 financing workshops on the subject at various places in the area (Q12, 21). Some activities are carried out under UNEP's Rural Energy Project. Also the WHO and UNICEF, as well as the OECD Development Centre have shown interest (Q20).

It is only very recently that the first detailed studies on the economic feasibility and the social acceptance of bihugas plants have been made (R3, 4, 6) and it is too early to formulate any definite conclusions as to the "appropriateness" of bihugas plants. However, it is significant that the first proper evaluatory studies were made more than 30 years after the large scale development and introduction of these techniques in many different countries.

1 .5 Purpose and outline of this review

It is against the background of the compilation of quotations given in the two previous sections that this review of biogas on farms should be placed. Over the past five years, many decisions have been made and many more will be made, by governments and international agencies concerning projects and programs involving anaerobic digestion. These decisions may perhaps be characterized as follows:

(a) they involve large sums of money;

(b) they are usually based on little knowledge of the technical aspects of the process of anaerobic digestion, and very little knowledge of the macro- and micro-economic, as well as socio-cultural aspects of introducing anaerobic digesters in rural areas;

(c) the decisions are being made in an atmosphere of romanticism and almost mythical ideas about a process alleged to produce fuel and fertilizer from waste, free of charge.

This review of the early history of small-scale digesters may be of some help in providing a more thorough and balanced picture of the state and status of technology of small-scale anaerobic digestion. This may be of use for both decision makers and people involved in R & D concerning small-scale digesters. For the latter category, if may be of interest that a large number of non-English publications is reviewed.

From the fact that only the literature until 1970 is covered, it does not follow that only a historical record is presented. Although recently there has been an enormous increase in the interest in anaerobic digestion, there has been hardly any addition to our general knowledge of small-scale anaerobic digesters since 1970. In fact most people concerned with the subject now know less about it than, say, the people concerned with the subject in 1955 in Germany. Therefore, where appropriate, assessments and suggestions for further research and such like, should be understood as being relative to the situation now (and not as of 1970). Since 1970, there has certainly been some progress in the theory of anaerobic digestion (microbiology, biochemistry). This knowledge is pre-supposed and freely used in the review.

2. VARIETY OF INTERESTS IN ANAEROBIC DIGESTION

2.1 Classification of anaerobic systems

Many people interested in some aspect of anaerobic digestion do not appreciate how great the number of publications is in other branches of the subject, or from countries other than their own. Also, a lot of confusion is caused by the fact that it is not always realized that the interest in anaerobic digestion may arise for quite different reasons. The following classification can be made with respect to the nature of the systems studied.

(a) Model systems: the kind of microbes involved, the kinetics of substrate consumption, parameters affecting gas production, growth rate of bacteria, antagonistic and symbiotic relations, and so on. This is the microbiology and biochemistry of anaerobic digestion, a priori relevant to all applications. Most work has been carried out by sanitary engineers, in connection with municipal digesters, and animal physiologists interested in rumen digestion. After an early interest around the turn of the century, microbiologists lost interest in anaerobic digestion, probably because of the complexities of mixed cultures: Methanogenic bacteria could not be isolated and plated out like other bacteria.

(b) Anaerobic digestion of food in animals, in particular, ruminants. There has been a long-standing interest in this, which was pursued rather independently from other interests in anaerobic digestion.

(c) Septic tanks. This is the oldest application of anaerobic digestion to waste treatment. Septic tanks have been installed at isolated dwellings all over the world. However, there has been very little systematic research in connection with septic tanks. In the conventional septic tank, there is no gas collection. Recently there have been proposals for various "integrated" systems, combining latrines with anaerobic digestion of night soil and gas collection, or growing fish on night soil (an old Chinese practice). This development is not reviewed here. See further (D27).

(d) Municipal digesters: anaerobic treatment of the spent sludge of aerobic treatment steps, sometimes also of other sludges, from sedimentation tanks or ponds. Of these, there are thousands of plants all over the world at the sewage works of large cities. Most of the research concerning anaerobic digestion has been carried out in connection with this application, since 1900. Nevertheless, the design and operation of sludge digesters is still mainly a craft. This area of interest is briefly reviewed in section 2.2.2.

(e) Anaerobic digestion of organic materials in the soil. Interest in this derives from the attempts to improve the effect of manure on the fertility of the soil.

(f) Bihugas production on the farm: anaerobic treatment of animal and vegetative wastes on the farm such that, besides manure (the traditional use of animal and vegetative wastes), methane gas is produced that can be used for cooking, lighting, and heating on the farm. It is this application of anaerobic digestion that is the main subject of chapters 3-6.

(g) Waste treatment of the agro- and food industry: anaerobic treatment of various types of concentrated organic wastes. Similar to the situation at sewage works, the interest is in the reduction of suspended solids and odour. The output of gas and "synthetic" manure † are only of secondary interest. The state of the art in anaerobic treatment of animal wastes and various organic industrial wastes, is summarized in sections 2.2.4 and 2.2.5.

(h) Upgrading of low-calorific energy sources. This is quite an inhomogeneous category. In some cases the prime motivation is waste treatment, for example, with regard to anaerobic digestion of refuse (see on this section 2.2.3). In other cases, the substrate to be used for anaerobic digestion is in fact used as an energy source, for example, bagasse or peat (see section 2.4). There is one case in which this category overlaps with biogas production on the farm: in particular in India there is widespread use of cow dung as a fuel (see section 3.6).

(i) Anaerobic digestion in connection with algae ponds. This is part of the general interest in photosynthetic reclamation of wastes and other "integrated" bio-systems (cf. section 2.4.5).

(j) Anaerobic treatment of dilute waste waters, for example domestic sewage. The fact that the waste water contains relatively small amounts

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† In the literature, the meaning of the terms "manure" and "fertilizer" is often ambiguous. In this review, the term "dung" refers to animal excreta: cow dung, horse dung, and so on. The term "manure" refers to the mixture of dung and straw that is commonly obtained when animals are kept in stables. The term "synthetic manure" includes any fertilizer that is obtained by some sort of processing of vegetative and/or animal organic wastes before it is applied to the soil. It refers in particular to manure that has been processed under aerobic and/or anaerobic conditions. Synthetic manure always contains both humus and inorganic fertilizers, in particular nitrogen. See also section 2.3.2 and chapter 5.

of organic material creates specific problems for a reactor design for this application (B14).

(k) Anaerobic digestion of specially grown "energy-crops". In this case, the sole interest is in energy production (see section 2.2.4).

This review is only concerned with bihugas production on the farm. It seems, however, appropriate to indicate briefly the developments in other areas where anaerobic digestion finds application.

2.2 Waste treatment

2.2.1 Introduction. Major areas where anaerobic digestion has found or may find application as an appropriate way of waste treatment are: sewage works, domestic solid wastes (refuse), large-scale animal waste, and industrial organic wastes (mainly food industries). Although in all these cases, the prime motivation is waste treatment, the production of gas during anaerobic digestion plays a role in the economic comparison with other alternatives of waste treatment. All these applications are basically large-scale. The use of septic tanks (not further reviewed here) is different, in that it is small-scale waste treatment, without gas collection.

2.2.2 Domestic waste waters (B1, 3, 11, 13). Until about 1935, the process of anaerobic digestion used at sewage treatment plants, passed through various stages of development. After that, further progress was made in control and sizing, but no major innovations were introduced. Sanitary engineers began to be interested in anaerobic digestion about 1895, when Cameron, the city engineer of Exeter (England) introduced a way of septic treatment which greatly reduced the suspended solids content of the effluent, as well as the severe odour problems at his plant. By 1905, most British and German sewage works had introduced similar improvements. Technological development from then on was rapid, first in England and Germany, a little later in the USA. Between 1907 (the first Imhoff-patent) and 1925, numerous patents were issued for the design of tanks for anaerobic digestion. Originally, these were non-heated, single stage, digesters which were operated at retention times of 30-90 days and loadings of 0.5-1.5 kg (VSS) m^{-3} d^{-1} (VSS = Volatile Suspended Solids). Soon heat was applied to keep the digesters at 30°C. Together with major design improvements, this led to various types of high-rate digesters, operated at retention times of 10-20 days and loadings of 1.5-6 kg m^{-3} d^{-1}.

Cameron is usually quoted as the first to collect the digester gas (in 1895) and to use it to light some of the street lamps in Exeter. However, production of methane at sewage plants has never been the prime interest. In fact, gas collection is only possible with large installations; the quantity of gas produced is then enough for the necessary engine power at the plant to drive pumps, and to heat the digesters. Of course, the significance given to gas production has been a function of the general energy situation. For example, in 1951, the 48 largest sewage works in West-Germany produced all together 16 x 10^6 m^3 gas per year. Of this amount, 50% was first compressed and then sold, and 30% was sold directly to the city gas works (C27). But nowadays this gas is only used for internal purposes. The maximum gas production at a sewage plant is in the order of 0.03 m^3 per capita per day, which is negligible compared to total energy consumption in industrialized countries.

Similarly, the production of compost or synthetic manure has never been a prime interest of sewage treatment plants. Because pathogenic bacteria, viruses, protozoa (cysts) and worms (eggs) can survive the various treatment steps at a sewage works, only heat-dried surplus sludge can be considered a completely safe fertilizer. In densely populated areas, sludge disposal of sewage plants is nowadays a major problem.

From the earliest beginnings, the suggestion has recurrently been made that sewage works and greenhouses should be combined, the latter using the surplus sludge and gas (both for heating and as a carbon dioxide source). But this concept has never been considered feasible enough to try out on a significant scale.

In Japan, China, occasionally in India, and perhaps at other places, anaerobic digestion tanks are (or have been) used for direct treatment of night soil, as distinct from anaerobic digestion of primary or secondary sludges obtained from sedimentation of aerobic treatments.

2.2.3 Domestic solid wastes (C1-10). Over the years, three distinct periods can be identified in the interest in anaerobic digestion of domestic solid wastes.

(a) The addition of ground garbage to sewage treatment plants started in the USA in 1935 (at Indiannapolis). Between 1938 and 1942, in a number of other places, the same treatment was applied. The digestion, as such, did not cause much problem - in fact the specific gas production and suspended solids reduction were usually higher for a mixture of sewage sludge and organic refuse, than for sewage sludge alone (C1-3). However, two main problems caused the disappearance of this interest by 1946: the very labour intensive loading procedures, and the problems with more resistant scum layers and various floating materials (C3). As we shall see, the latter was also one of the main problems in applying anaerobic digestion to agricultural wastes.

(b) During, and just after the second world war, there was a brief interest in this possibility in West Germany. Whereas in the USA, the motivation was primarily to find an economic solution for a waste problem, in Germany there was a specific interest in energy production (G2-6).

(c) Since about 1970 some interest in anaerobic treatment of solid wastes arose again, as a possible contribution to solving the more and more pressing problem of how to dispose of the refuse produced in industrialized countries. Over the past 10 years, environmental agencies in the USA have subsidized numerous investigations concerning the question of what to do with refuse. Although it has been said that the anaerobic "process could have significant merit in treating the organic fraction of the solid waste stream" (C5), it is generally ascribed an unimportant role compared with other alternatives (such as landfill, composting, incineration, pyrolisis, mixing with coal to generate gas, wet or partial oxidation, or even protein production).

In Table 2.1, a few selected data are given on the anaerobic digestion of various domestic wastes. Refuse in industrialized countries contains about 40-50% paper and 20-25% garbage (food wastes, leaves, grasses). Therefore, theoretical research on the digestibility of such mainly cellulosic materials (C6, 9) under the heading of refuse is also relevant to anaerobic treatment of agricultural wastes.

2.2.4 Large-scale animal waste disposal (C27). With the rapid increase in size of dairy, hog, and poultry farms since World War II, the waste management on such farms has become more and more problematic. The increase in size together with environmental legislation sets more and more restrictions on odour production and acceptable ways of disposing of the excreta (C22, 23, 26).

Starting in the early sixties (L11), and rapidly increasing since 1970, this situation generated, apart from other studies, a large research input in the anaerobic digestion of such wastes in the USA, later followed by Britain, New Zealand, Canada, and more recently, The Netherlands and Germany. Publications on this subject are covered in the annual reviews on anaerobic digestion in the Journal of the Water Pollution Control Federation. This literature is not covered here.

For animal wastes, the question does not arise as to whether they can be digested anaerobically. Technically, the process is more or less under control (in particular for hog farms), although specific provisions may be necessary (for example, preventing ammonia inhibition in the case of poultry wastes) and sophisticated control is necessary due to the sensitivity to disturbances, in particular at high loadings.

Practical realizations of anaerobic digestion for large-scale animal waste

TABLE 2.1. Some selected data on the anaerobic digestion of various domestic wastes. Accurate data, both for laboratory and large-scale digestion, are scarce and incomplete. In the table, data are given for the specific gas production in m^3/kg dry matter, α, and/or the suspended solids reduction in % weight, β. In most cases it is not known whether the dry matter refers to total solids, or to organic solids. Unless otherwise indicated the temperature, T, is (expected to be) 30-35°C. All laboratory data are for batch experiments, with a duration of 30-70 days. Large-scale data are all for digester tanks at sewage works. The retention time, t, is usually not given, but will be in the order of 30 days. Under "remarks", the parameter n refers to the number of plants on which the data given are based. The methane content of the gas is always between 50 and 80%.

type of waste	$\alpha(m^3/kg)$	β(%)	remarks	references
(a) laboratory data				
filter paper	0.68-0.86	77-98		L7,9, G4
newspaper	0.3	34		L7
toilet paper		50-65		L7
mixed paper	0.23			G33
cotton, textile	0.28	78	α(G33), β(L7)	G33, L7
vegetable wastes	0.44-0.6		lower value for India	G33, N16
organic refuse	0.26		t=10 days, α=0.46 at 60°C	C6
grass	0.22-0.49		see table 4.4	
leaves	0.1 -0.3		see table 4.4	
weeds	0.02-0.43		see table 4.4	
night-soil	0.4 -0.7	50-80	Indian diet, T=20-26°C	N36,44
sewage screenings	0.31-0.37			L7
(b) large-scale data				
sewage sludge	0.1 -0.6	24-75	n=20 (USA, Germany)	B8, G4
sewage sludge + garbage	0.1 -0.9	30-60	n=9 (USA, Germany, Netherlands)	B8, C2, G5
garbage	0.3 -0.7		n=4 (USA + 1 Netherlands)	B8, G5
sewage sludge + garbage + paper	0.2 -0.5		n=1 (Netherlands, 1944)	G5
sewage sludge + industrial wastes	0.1 -0.6	24-64	n=24 (USA, Germany)	B8, C44
leaves	0.32	30	n=1 (Germany, 1929)	G4

treatment have been rare up till now, because of economic restrictions. A number of recently published (socio-) economic assessments, all for North America, differ in the details of their conclusions (C21, 23, 25). Some expect the anaerobic process to be economical above 3000 (large) animals (C25). Others (C21) start their calculations only at sizes of 100,000 cattle feedlot. However, all agree that the process has no significance as an economic fuel source. The only reason why it may become feasible is on a waste management basis, where it should be compared with other alternatives.

In tropical countries, the evaluation will, a priori, be more favourable. Because of the high ambient temperatures, less energy for heating is necessary (perhaps even, the operation is possible without heating at all). In this case, the volume of the digesters has to be sized for operation at the lowest temperature, and fluctuations in temperature may adversely affect digester behaviour. No general conclusions are possible as to whether one should work in the tropics at 30°C or ambient temperature. Secondly, in industrialized countries, a disadvantage of anaerobic digestion, compared with other alternatives, is its labour-intensity; this may be less important in some tropical countries. A small number of anaerobic digesters is known to operate reasonably to satisfactorily on large hog farms in The Philippines and Taiwan, and perhaps other countries.

2.2.5 Industrial wastes (C41-53). Although industrial wastes are usually quite different from agricultural wastes, a brief indication of the history of anaerobic digestion in this area may add to the general picture. Below, a few remarks on the history up till about 1960 are made. For later developments, see the Proceedings of the regular Industrial Waste Conferences, organized at Purdue University, and the annual reviews on anaerobic digestion in the Journal of the Water Pollution Control Federation. A recent review article on the subject is not available.

After the rapid development of information on anaerobic digestion between 1880 and 1905, the idea of using anaerobic digestion for treating industrial wastes has been repeatedly taken up all over the world. Without much continuing success, large-scale applications started in 1914 in The Netherlands, where the process was used for treating the waste waters of a straw-based factory. The plant operated satisfactorily for some time, but did not turn out to be economical. There were also problems of keeping the process under control. In 1924, anaerobic treatment of paper mill waste waters reached the pilot plant stage in Germany, but was not taken any further. In 1928, a patent was issued in The Netherlands (C41) to a company working in Indonesia. It gives a detailed description of how to carry out thermophilic or mesophilic digestion of molasses. From the text, it is apparent that there had been close

TABLE 2.2 Pre-1970 references to the digestibility of various (agro-) industrial wastes. All data are for small-scale laboratory or pilot-plant scale experiments; α and β as in table 2.1. Under "remarks", B indicates batch experiments, C indicates semi-continuous experiments, t is duration or residence time, η is the loading expressed in kg dry solids per m^3 reactor volume per day. Unless otherwise indicated the temperature is 25-30°C. As in table 2.1 the methane content of the gas is always between 50 and 80%. Apart from the wastes mentioned in the table the following wastes have also been shown to be suitable for anaerobic digestion: pea blancher, food canning (mixtures), citric acid, starch, natural gums (chewing gum), rubber, straw board, malt syrup, molasses, butanol and aceton fermentation products, antibiotics and vitamins, paper mill white water, wood scourings, organic dyes.

type of waste	α(m^3/kg)	β(%)	remarks	references
(a) animal and dairy wastes				
cow paunch	0.30		C, η = 4.5	L7
hog paunch	0.56		C, η = 6	L7
packing house screenings	0.40		C, η = 5.6	L7
slaughterhouse, various	0.1 -0.46		B, C	G33, L7
whey	0.7		C, η = 2.1	L7
buttermilk	0.6 -0.8		C, η = 3.2	L7
skimmed milk	0.6		C, η = 1.7	L7
dairies, various	0.7 -1.0			B16, G33
(b) vegetable wastes				
chicory	0.6		C, η = 2.6	L7
artichoke top flour	0.53		B, t = 21 days	L9
artichoke top flour	0.53		B, T = 53°C, t = 14 days	
extracted artichokes	0.53-0.65	34	B, C, η = 1.7, t = 60-100 days	L7
(c) fruit wastes				
citrus pulp	0.4 -0.7	50-90	t = 60-180 days	L7
apple waste	0.31			G33
orange juice	0.48		T = 37°C	G33

TABLE 2.2 (cont'd) Pre-1970 references to the digestibility of various (agro-) industrial wastes.

types of waste	$\alpha(m^3/kg)$	$\beta(\%)$	remarks	references
(d) other agro-wastes				
sugar beet waste	0.76		C, η = 1.3, t = 30 days	L7
beet pulp	0.40		B	G33
sisal waste	0.38			G34
(e) fermentation wastes				
beer slop waste	0.64	60	C, η = 0.6	L7
breweries, various	0.43-0.56	90(?)	B, C	B11, G33
distillery wastes	0.75		C	L7
yeast	0.49		B	G33
partly digested grapes	0.14		B	F21
(f) paper industries				
paper pulp	0.16		C	B11
waste water paper factory	0.25		B	G33
cook liquor	0.48		B, t = 27 days	L9
(g) chemical industries				
stainery	0.13	28	C	B11
tannin chips	0.06		B, t = 32 days	L7
valonea	0.02		B, t = 84 days	P15
tanneries various	0.10-0.26	10	C	B11, G4
potato starch	0.78			L7, G34

contacts with the microbiologists at Delft University of Technology (A3, 4).

In 1926, a long-term research programme, concerning the feasibility of anaerobic digestion for treating industrial waste waters, started at the Illinois State Water Survey Division. The programme was headed by A.M. Buswell. Starting in 1928 with a paper by Neave and Buswell concerning the disposal of distillery slop by anaerobic digestion (C42), numerous publications from this project emerged. The publications up till 1938 have been reprinted or are summarized in (L7), together with unpublished material. On the whole, the programme was not successful. The first pilot-plant stage was not reached until 1936. As far as is known, not one large-scale plant has ever been put into operation as a result of this programme. Industrial wastes that have been found to be suitable for anaerobic digestion are listed in table 2.2. It can be seen that Buswell and collaborators (reference L7) made a large contribution to our knowledge in this area. However, many of their data are only of qualitative use, because of the rather unsystematic way in which the experiments were planned and data collected. At the Illinois State Water Survey Division, work was also carried out on agricultural wastes (which is summarized elsewhere in this review).

In the period of 1930-1950, interest in anaerobic digestion of industrial wastes in the USA, of which the above forms the greater part, was mainly stimulated by the overloading of municipal sewage works with industrial waste waters (C43). For example, in 1947, cheese whey - until then fed to the sewer - was transported in trucks from a factory to the sewage works at Marion, mixed with garbage (cf section 2.2.3) and fed directly into a sludge digester (C44). From 1950 onwards, food industries were themselves increasingly forced to dispose of their own wastes, and combining industrial wastes with sewage sludge or garbage was not considered further.

It is difficult to assess to what extent large scale anaerobic digestion of industrial wastes has been applied in the first part of this century. Around 1930, anaerobic digestion of distillery wastes has been seriously considered in Britain (D2). It is said that in 1937, anaerobic digestion plants treating yeast wastes were in operation at Slagelse (Denmark), Rotebro, and Narjo (both Sweden), producing 1000-1500 m^3 gas per day (B12, C53) but no further details are available. Also anaerobic plants treating antibiotic and vitamin wastes were in operation in Belgium and Japan, whereas plans to install such plants in the USA failed (C51).

The first industrial application that is reasonably documented is the treatment of the wastes of a meat packing factory in Minnesota (USA). A pilot plant started in 1950, and the full-scale plant started operation in 1955, according to a publication of 1958 (C50). Later publications (C53, B12) quote

1959 as the year when full-scale operation started (processing 5000 m^3 waste water per day), which casts some doubt on the success of this project. In a review written in 1963 (C53), quoting 57 references on the anaerobic digestion of industrial waste waters, it is said that full-scale operations in the USA exist for yeast, butanol and aceton fermentation products, chewing gum, and meat packing wastes. But details are hard to come by, and it would seem that at present (i.e. 1978), the situation is not very different from that of 30 years ago.

For tropical countries, the major potential area of application is for treating wastes from the industries based on sugar cane, in particular the liquid wastes from distilleries fermenting molasses. Interest in using anaerobic digestion for this purpose started in India around 1960 (C52, N34). At the moment, numerous institutes in a large number of tropical countries are interested in this possibility, but as yet, no full-scale plants seem to have been put into operation.

2.3 Anaerobic digestion and soil fertility

Basically, there are two ways in which anaerobic digestion is related to an interest in soil fertility.

(a) soil conservation and fertility are dependent on the way plant and other organic residues are decomposed in the soil; in certain circumstances this decomposition may take place under anaerobic conditions;

(b) anaerobic conditions may be used in processing manure before it is applied to the soil as fertilizer.

2.3.1 Anaerobic decomposition in the soil. In moderate climates, most soils are anaerobic, but they are of little agricultural interest. Before the war, some research was carried out at the New Jersey Agricultural Experiment Station (E2) and Rothamsted Experimental Station in England. At the latter Station, a large project was carried out by Acharya (E5), who later was active at the Indian Agricultural Research Institute in the development of small cow dung digesters (see section 3.6). In areas where rice is grown under swamp or water-logged conditions, such as South East Asia, anaerobic decomposition in the soil is much more important. In total, very little research has been carried out on this aspect of anaerobic digestion.

2.3.2 Synthetic manure. Significant interest in methods to improve traditional ways of manure handling started early in this century. In processing manure (solely or mainly derived from animal excreta), three aspects are predominant: (i) the processing time interrelated with the costs of handling, (ii) the processing time and the temperature (control) in connection with the removal of pathogens (and to a lesser extent, weed seeds), (iii) the nitrogen loss during processing. From the very beginning, the advantages of anaerobic digestion (without collecting the gas) after a brief aerobic pre-digestion (which raises the temperature) have been recognized: less nitrogen loss, more weeds and pathogens killed.

The work carried out by Richards and Hutchinson at Rothamsted, and even more, the so-called "Edelmist" ("Noble-manure") process patented in Germany in 1921 (E1), was taken up in many countries. For example, the latter process was tried out by Scott (E7) at the Cheelos University in China; the results were promising, but the project was terminated with the Japanese occupation. As might be expected, synthetic manure processes, developed in Europe, could not be transferred to tropical regions without being adapted to local circumstances. This is apparent, for example, from work carried out in India between 1930 and 1939 (E3-6). The later interest in bihugas digesters in India derived from a shift in emphasis from the soil fertility aspects to the energy prospects of anaerobic digestion of manure. This is most apparent from the publications of Acharya (E5, N1,8-11).

Perhaps the most fundamental (as distinct from economic) problem in the application of (synthetic) manure to the soil, is the health aspect: smell, fly-breeding, and pathogens present in the excreta of the animals. This is an even more pressing problem if night-soil is also to be used. The health aspect is a strong reason to consider in the first instance thermophilic anaerobic digestion, and this has occasionally been stressed in the literature during the last 40 years (C24, E6,8), but with little effect.

2.4 Anaerobic digestion used in energy production

In section 1.1, the early interests in the possibilitv of applying anaerobic digestion to produce a high-quality fuel from organic (waste) material were described. A priori, organic materials can be processed to fuel in numerous ways. Some of the more important possibilities are: (i) direct burning, (ii) charcoal (from wood), (iii) anaerobic digestion to produce methane, (iv) fermentation to alcohol, which can be used as a liquid fuel, (v) pyrolisis (thermal decomposition in the absence of oxygen, hence partial combustion, to methane, carbon monoxide and hydrogen; pyrolisis to oil and tar is also possible), (vi) hydrogasification (part of the feed is converted to hydrogen by partial oxidation, or steam reforming, and the hydrogen-rich gas is then used to hydrogenate the remaining feed to yield a high methane production). All processes mentioned are subject to strong economies of scale (cf chapter 6). The last process mentioned can only find application on a very large scale. These alternatives to anaerobic digestion will not be discussed. However, it should always be kept in mind that the feasibility of bihugas production is to be seen relative to other uses the organic material may be put to, as well as the price of various fuels in the environment considered.

2.4.1 Energy production on the traditional farm (i.e. excluding the bio-industry). Anaerobic digestion has been considered in this context in the USA in the 1930s (L3, 5), in various Western European countries just after World War II, in India from 1940 onwards, and more recently, in numerous developing countries. This category is discussed in more detail in chapter 3.

2.4.2 Fuel from wastes. Perhaps the first serious consideration of deriving methane from large masses of waste materials was made in 1920 in India. On the West Coast of India, there are no coal fields, but there are vast amounts of cellulosic waste materials (such as banana skins and stems). It was therefore suggested that this could be a major fuel source (D1).

On the whole, however, there has been little interest in this application of anaerobic digestion. The recent energy crisis has changed the climate of opinion, and the possibility of fuel production from domestic, animal, and in particular, wood wastes (in the lumbering industry 50% of the biomass is considered waste) has been investigated in North America and elsewhere (D3-7). In the case of domestic and animal wastes, the evaluation, of course, also has to take into account the waste treatment aspect (see sections 2.2.3 and 2.2.4).

Although there are differences between the various evaluations, it seems that there is communis opinio on the major conclusions: (i) fuel from waste asks for high investments and presents difficult and costly handling problems; for this reason, this option is only feasible (if at all) if the process is carried out on a very large scale; (ii) anaerobic digestion ranks low when compared with other processes; (iii) even if all wastes are processed into fuel, the contribution to the total fuel consumption of industrialized countries would be at the most one per cent.

2.4.3 Upgrading low-calorific fuels. Around 1917, research was carried out in the U.K. in an attempt to ferment peat to methane. This proved to be unsuccessful, probably because there is very little cellulose in peat (D2). The possibility of anaerobic digestion to upgrade peat and soft-coal has also been considered in the USSR. Recently, the interest in anaerobic digestion of peat has increased considerably (D12).

2.4.4 Energy crops (land). As a kind of natural consequence of considering fuel production from agricultural wastes, proposals have been made to grow crops only for the sake of converting them into biogas (D7-10). In general, the financial return on a fuel crop per acre is substantially below that of a food crop, because of the prevailing market conditions with respect to food and fuel (D6).

In comparing the alternatives of producing fuel from vegetative materials, the situation is different for wastes and for specially grown crops. In the first case, the major economic factor is the investment costs for the processing installations. In the second case, the major cost component is the plant material itself.

At present, fuel from energy crops is not feasible under normal economic conditions. However, agricultural science has always been directed to maximizing protein yield of plant species. One may expect therefore that still considerable improvements are possible in maximizing biomass production during the growing season. One may further expect that methane production from energy crops may become attractive in the first place for rural areas (which favours small- and medium-scale production) in tropical countries (as the climate favours anaerobic digestion), where the residue can find application as fertilizer. The major competitor in this context would seem to be alcohol production from specially grown crops; and in fact, Brazil is engaged in a large programme to produce alcohol that way (D11).

2.4.5 Energy crops (water-grown plants). As early as 1929 (D21), it was suggested that methane could be obtained from the water hyacinth. From 1960 onwards, there has been a steadily increasing interest in the use of water hyacinths and various algae to process the energy of the sun quickly into food and fuel. There is a complicated interrelation of waste treatment, food, and energy production aspects. For example, algae may be grown on waste waters and fed to fish (D27), in which case, neither anaerobic digestion, nor energy production is considered.

Compared with land energy crops such as Napier grass and Kenaf, algae give similar amounts of organic material produced per acre. The fact that water-grown plants may contain up to 95% water, means that they are less suitable as a source of fuel when thermal processes have to be used. If energy is to be derived from water-grown plants, probably anaerobic digestion is at the moment, the only option. At present, experiments with algae ponds combined with biogas plants are being carried out at a large number of places in tropical countries. For the time being, it is difficult to judge whether this has some prospect for successful adoption by the population of rural areas. Using conventional standards of economic evaluation, it appears that a 100 ha algae/methane farm could be economical if the methane is used for local needs

(D28). At least 1000 ha are necessary to produce commercial methane (to be sold in cylinders or to the chemical industry).

3. PRE-1970 HISTORY OF SMALL-SCALE DIGESTERS ON THE FARM†

3.1 France and Algeria

As has been stated in section 1.1, by 1883, attention had already been drawn (by Gayon, a pupil of Pasteur) to the fact that one could use the anaerobic digestion of manure as an energy source. However, it seems there was no response to his suggestion. Gayon had presented his results in Bordeaux (before Pasteur presented the subject in Paris), in a lecture for the "Société des Sciences physiques et naturelles de Bordeaux" (the room being lighted by a small biogas light). In 1931, Dubaquié (F2) gave a lecture to the same Society, reporting a few laboratory experiments on the digestion of manure, and making a suggestion as to how to design digesters to produce biogas on the farm, as well as stressing the fertilizer value of the manure so obtained. This lecture also failed to induce any interest in the matter, as is apparent from a note Dubaquié presented in 1943 to the "Académie d'Agriculture de France", in which he reviewed the early interests of Davy, Gayon, and himself in the subject. This note was a reaction to a note of Coupan to the same Academy, presented October 14, 1942, which was the first official attention given to the work of Ducellier and Isman (F4).

Isman was the professor and Ducellier the head of the laboratory at the "Ecole Nationale d'Agriculture" in Algeria. They started work on anaerobic digestion in 1938. Although this work was more or less interrupted (between 1939 and 1942) by the war, their impact in France was at once quite substantial. They applied for patents in France in 1941 and 1942 (F3, F5) and in 1942, their first reports started to circulate in France on a large scale. They were awarded the "Médaille d'Or" by the Société d'Encouragement pour l'Industrie Nationale", and the "Ecole Nationale d'Agriculture" [the same institute where Délérain worked on anaerobic digestion 60 years before (A2)], at Grignon (France), started work on the subject in September 1942 under the direction of Guérillot (F9) but this research interest never became very apparent.

The digester design Ducellier and Isman introduced was basically very simple

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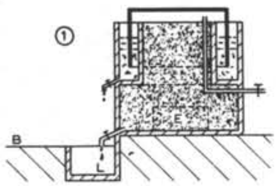
†An abridged version of this chapter, including the figures, has been published in Tropical Science.



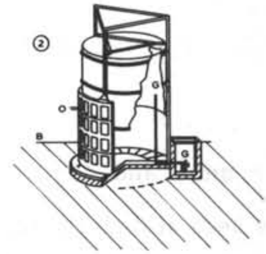


FIG. 3.1. The first digester used by Ducellier and Isman in Algeria from 1938 onwards (type: "Algeria"). The design reproduced here is taken from a secondary publication of 1948 (F14). It seems probable that the water-seals for the metal cover are not on scale. When digesters were installed in France, according to this design, they were usually equipped with small water-seals at the top against the outside wall of the digester (see pictures in F27-29). The digester itself is made from concrete or masonry, usually in rectangular form (a typical size being 2x2x2 m^3). There are no provisions for mixing or heating. The digester is filled with manure from the top (after the metal cover has been removed), to which 10-25% water or, preferably, muck water (or similar liquid which may act as inoculum) is added. After two to three months, first the liquid is drained (L) [which may be reused again] and then the digested manure is taken out via door E. The labour intensity of this digester is self-evident.

FIG. 3.2. The digester produced commercially by the "Sociètè Centrale d'Approvisionnements aux Agriculteurs de France" (SCAAF) from 1949 onwards (type: "Paris"). The SCAAF obtained the licenses of the Ducellier-Isman patents (F3, F5) and combined these with their already patented design of a manure container (F7), using pre-fabricated elements of reinforced concrete to reduce costs of materials and construction. The design as reproduced here combines the digester and the gas holder. However, most SCAAF digesters have been installed with a separate gas holder, as this lessens the heat loss from the digester to the environment. The operation is similar to that of the "Algeria" type. Loading and unloading is via the top (i.e. cover or gasholder have to be removed). The manure is topped up with 25% liquid, which at the end can be drained (not depicted in the figure). Most digesters of this type had a volume of 10 m^3. Some of them were equipped with hot water heating pipes in the digester, but usually a layer of manure was piled against the walls (see Fig. 3.4).

(see Fig. 3.1). More important was the concept behind the design, which is, that anaerobic digestion of agricultural wastes is only feasible if preceded by an aerobic predigestion. The latter has two functions: to prevent acid fermentation (cf section 4.5.2) and to produce the heat necessary for the aerobic digestion. The intention was that extra heating would not be necessary. Of course, the fallacy here was that the further north (geographically) the more heating required.

Apart from the first impetus they gave, the direct influence in France of

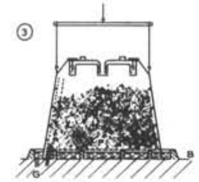


FIG. 3.3. The digester patented by Massaux (F23) in 1952 (type: "Lyon"). Unlike the previous two digesters, this one operated with solid manure in order to improve the heat economy and to reduce labour. Solid manure is packed loosely in the container so that heat insulation is better than with moist or liquid manure. Also, predigestion will be more homogeneous for solid manure. The container can be removed completely so that "unloading" is simpler. The water seals at the top and on ground level are filled with liquid manure which can be circulated through the manure heap using the top water seals as overflows. Digesters have been installed where this is done manually and also with a system similar to that depicted in Fig. 3.6, (compare also Fig. 3.17), such that the over pressure in the digester during the night pushes the muck water out of the digester at the bottom and back to the seals at the top. [The idea of recirculating the muck water, which serves as an inoculum, was first introduced by Ducellier and Isman (F8).] No reports are available as to whether this worked satisfactorily. Of this design, about 800 were installed in the Lyon area by the firm "Salubra" and about 40 in Italy by the firm "Biogas" (see section 3.3.2). When operated properly, gas production was 0.4 m^3/m^3. [A more sophisticated design based on the same principles was already patented in Switzerland in 1943 (K31). This seems to have been unknown in France.]

Ducellier and Isman was small, although with varying intensity. They continued working on anaerobic digestion in Algeria until about 1958 (F44, 46, 48). Work was carried out on the digestibility of various vegetative wastes (summarized in F20), on the microbiology of the process (F46, 48), and on the large-scale digestion of manure and vineyard stalks. By 1956, the Agricultural Institute of Algeria operated eight digesters, with a total capacity of 300 m^3, using the manure from their stables. They had a gas storage capacity of 1000 m^3 and facilities to compress the gas for use in tractors (F44). In 1962, Ducellier wrote a small book summarizing the work on anaerobic digestion in Algeria (F51). Probably because of the political turmoil, this was never published.

In France, probably, a large number of farm digesters were built between 1942 and 1946, that is, before a large number of publications started to appear. The total number of digesters in France in about 1949, is variously quoted as 500 to 1000 (F16, 17, 24-27). No reliable data are available, and it is possible that the actual number of digesters in operation has never been higher than 100 at any time. Only batch digesters were built in France and almost

TABLE 3.1. Meaning of capital letters used in figures of digester designs (Figs. 3.1-3.34).

A,	aerobic pre-digester, mixing of fresh manure with water and/or straw and/or other vegetative materials;
B,	base, ground level;
C,	compost pit, soil-ready manure storage, spent sludge container;
D,	anaerobic digesting chamber containing pumpable manure;
E,	effluent, output, discharge;
F,	feed, input, intake;
G,	gas holder, gas storage, gas discharge;
H,	heat exchanger to heat digester contents;
L,	liquid manure (low suspended solids content), urine, muck water;
M,	mechanical agitation, stirrer;
O,	overflow;
P,	perforated plate, screen, sieve plate, draining holes;
R,	recirculation, agitation (mixing) by pneumatic or hydraulic means;
S,	spray, sprinklers, distributor for wetting liquid;
T,	thermometer, temperature control;
U,	undiluted (solid) manure (non-flowing);
W,	water used for thinning, water seals.

all of them of a small size (7-12 m^3). The basic design used was that of Ducellier and Isman (Fig. 3.1), who sold the right to use their patents to the "Société Centrale d'Approvisionnements aux Agriculteurs de France" (SCAAF). This organization subsequently concentrated on reducing costs by providing digesters made from pre-fabricated elements or reinforced concrete. By 1948, there were, most probably, about ten firms active in selling and constructing digesters. The variety of designs actually installed was basically determined by three factors: price and availability of construction materials, heating; and scum layer formation (which blocks gas release). The ways of dealing with the heating problem are summarized in Figs. 3.4 and 3.5.

A basic way of dealing with the scum layer problem is not to thin the manure with liquid. A design based on this idea was patented in 1952 (Fig. 3.3). Also, quite a number of sophisticated designs were proposed to deal in the most efficient way with the scum layer and heating problems (Figs. 3.6-3.8). However, of these more sophisticated designs, never more than two or three have been built and no performance data are available.

In the years 1950-1952, the firm "Salubra", which built the digesters patented by Massaux (Fig. 3.3) was very active in the Lyon area. The relation

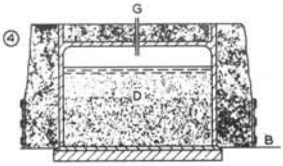


FIG. 3.4. Direct heating by means of aerobic digestion. Most of the digesters used in France were "heated" by piling layers of fresh manure around the digester, and also on top of the cover (through which heat losses are greatest). The following types have been reported in the literature: "Paris", having walls of reinforced concrete (see Fig. 3.2), manure layer of 80-120 cm; "Bassin de l'Adour", 6 m^3 digester produced commercially from waste (war-time) metal (F33); a number of designs of the firm "Salubra" (F9-11). Photographs of 2 digesters of 7 m^3 + gas holder of 7 m^3, and 3 digesters of 10 m^3 + gas holder of 10 m^3 heated this way are given, for example, in (F25). Instead of piling fresh manure around an anaerobic digester, one may attempt to use the heat generated in the digester during aerobic pre-digestion for near-by digesters in the anaerobic stage, Numerous layouts have been published (F5, 32, 33), indicating how two to six digesters can be arranged (usually, at least partly, sub-soil) and operated to have minimum heat losses and maximum profit of the heat generated during aerobic digestion. In transferring their technology from Algeria to the climatically different France, Ducellier and Isman patented this idea (F5). Later, the firm "Fermenclos", which was most interested in the fertilizer value of this residue, installed according to this principle, quite a number of groups of four digesters (F33). Groups of two or three digesters with one gas holder were most common (F25). Other firms that installed "Algeria" type digesters of this type were: "Soprodi" (F21), "Fumigaz" (P1), and "Lesage" (F25).

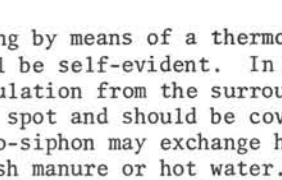


FIG. 3.5. Indirect heating by means of a thermo-siphon (natural circulation of liquid). The picture will be self-evident. In this case, thick walls are necessary to increase insulation from the surroundings. The metal cover is, also in this case, a weak spot and should be covered with straw or insulated in other ways. The thermo-siphon may exchange heat with different sources; most common is either fresh manure or hot water. The circulation of liquid will also have a mixing effect and may reduce the difficulties caused by scum layers. The digesters are usually made of bricks, a typical wall thickness being 22 cm. Thick wall digesters using thermo-siphons have been sold commercially by the firms "Somagaz", 2 m^3 digester (F12-14) and "Salubra",type "Metagaz", 8-15 m^3 (F33). No performance data of the heat economy have ever been published.

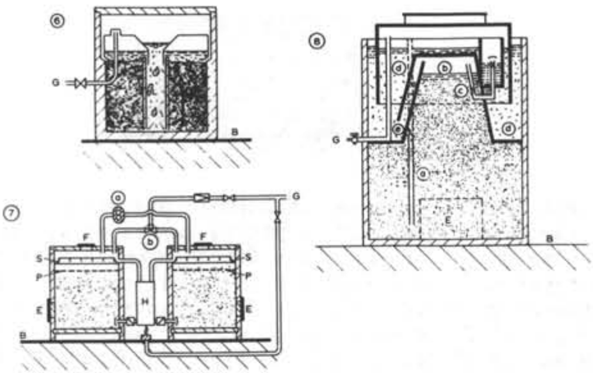


FIG. 3.6. Design with central chimney to facilitate natural mixing [adapted from (G58)]. The concept behind this adapted "Algeria"-design is that the liquid (manure), L, should circulate by going upward through the solid manure (which is contained in between two concentric cylinders) due to upward flow of gas, and falling down in the central chimney due to density differences. No heating is provided and loading and unloading is very labour-intensive. Note that this design has a fixed, albeit small gas holder. No separate gas holder is needed if gas consumption is steady. This design has been mentioned in the literature, but no reports of it actually having been in operation exist.

FIG. 3.7. Heating, mixing and scum layer destruction through enforced circulation of liquid. The picture is adapted from (G58); the inventor has been quoted to be Barboni (F33). No details are available on the actual operation of this sophisticated adaptation of the "Algeria"-design. By operating valves (a) and (b) in the appropriate way, a pressure difference is created between the two digesters. This enforces a flow of liquid through the heat exchanger and breaks up the scum layers by pressing them through the screens, P. The contraption, S, is meant to divide the liquid equally. It may be speculated that this design can only be feasible, if ever, on a large scale.

FIG. 3.8. Sophisticated "Algeria"-design, type "Boufarik" (as reproduced in F13). No moving parts are used in this design to prevent the formation of a scum layer, as follows: The gas production raises the pressure in (b), hence liquid is pressed through tube (a) into the reservoir (d); also the liquid level in the U-tube (c) falls. When the liquid level in (c) reaches the bottom of the U-tube, an unstable situation arises. Suddenly a large amount of gas escapes through (c), the pressure in (b) is released and liquid from (d) returns to (b) via (e). It seems that a digester of this type has been used successfully on a large scale (processing wine-marc) by Ducellier and Isman at Boufarik, Algeria (P22, 29). The design has also been tried out at the "Distillerie Coöperative d'Olonzac" (Herault, France), but apparently without success (F13, 22, 29).

between the patents of Ducellier and Isman, and SCAAF on the one hand, and Massaux on the other, is not clear. No reliable data are available on the number of digesters installed. According to the director of the Lyon area cooperative (La Coopérative d'Elevage du Bassin Lyonais) 1000 digesters of concrete (using waste iron and steel) were in operation in February 1951, and another 1000 were under construction (F25). However, according to Massaux, in an interview in 1952, 840 digesters were in operation in the whole of France - probably the latter number is still on the high side.

The digesters installed in the Lyon area by the provincial department of agriculture (Le Génie Rural) were subsidized for 50 per cent of the installation costs. However, it has been said that it was very common to submit falsified bills, stating higher amounts than actually paid, such that the farmer, in fact, obtained a fully installed digester without any cost on his own part. This may explain why there was such an intense interest on the part of the farmers. In fact, only 12 per cent of the requests for subsidy were granted. Neither before the decision was made to subsidize the installation of digesters, nor during this program, was any evaluation made of the socio-economic feasibility of the digesters. Probably, the possibility to obtain subsidy was stopped at the end of 1952, because no later reports of what happened in the Lyon area have been secured.

In fact, the interesting thing to note is that virtually no R & D work was carried out in France on anaerobic digestion. Apart from the experimental work of Ducellier and Isman in Algeria, there exist only two publications (F15, 31) reporting original observations. All other publications listed in the bibliography under France are basically promotion papers speculating on the virtue of applying anaerobic digestion on a large scale. On behalf of the Department of Agriculture, Carré and Vignerot studied the subject of biogas in general, starting 1945, and controlled experiments were carried out at L'Asile de Ville-Erard; but no results have been published.

Roughly speaking, the publications that appeared in the period 1947-1951, are describing what was the case by then, that is: digesters of various types that had been installed on farms and were operating with more or less success. The principles of anaerobic digestion laid out by Ducellier and Isman were repeated over and over again; the problems that had appeared in practice (in particular, the necessity of heating after all) were discussed in an optimistic way; and photographs and descriptions of the six or so most successful digesters were given. In general, the emphasis was more on what one could do with the gas than on how to obtain it. This boom of publications of the "Do you know that Johnson has a wonder on his farm?"-type culminated in the production of two small books in 1952 (F32, 33).

From 1951 onwards, there have only been promotion publications. Already by 1945, Ducellier and Isman (F9) had suggested that methane production from agricultural wastes might solve the world's energy problems. This point was stressed repeatedly. Other aspects that were equally stressed were: the support biogas could give to agricultural mechanization, and a more pleasant life for the farmer's wife (biogas replacing coal and wood).

Were it not for the insistence of two professors of agriculture, Ballu and Féraud, the history of anaerobic digestion in France might well have ended in 1952. Both had addressed the Academy of Agriculture of France on the subject before (F10, 26), but it was not until 1953/54 that they started their major attack. At the end of 1954 (F36) they succeeded in convincing the Academy to write a letter to the Ministry of Agriculture stressing the most promising potentials of this technology and asking them to have an official study made of the matter. In reply, the Ministry promised to make an inquiry among all the districts to find out how the digesters were working in practice (F37). As far as is known, no such inquiry has been made.

Perhaps one of the main reasons Ballu and Féraud could get some support for their pleas is to be found in their continuous emphasis on chauvinistic aspects, apart from other advantages of anaerobic digestion: Ducellier and Isman were the first to apply the process successfully, and now other countries, in particular Germany, were taking the lead with substantial support by the Government (or rather Marshall-Aid): "We must avoid the risk that Our Country, in the end, has to pay for the use of foreign patents to use on Our Own Soil, a French invention" (Ballu, 1955). Early in 1956, they convinced the Council of Presidents of Agricultural Associations ("Le Comité Permanent Général de l'Assemblée Permanents des Présidents des Chambres d'Agriculture") to form a working party on "manure gas". In the first two meetings of the party, they concluded that two installations had definitely proved, in long-term operation, the feasibility of anaerobic digestion (F44). The first was a rather large-scale operation (eight digesters of 13 m^3, further details in F38) at the Abbey of Monts des Câts. The other was a private one owned by the farmer Dammoneville (details on his digester in F42). However, in its assessment, economic and labour aspects were hardly considered by the working party, and the other 1000 digesters that were said to be in operation were not evaluated.

From the discussions before the Academy of Agriculture in 1956 (F41), it appears that in France, no systematic study was carried out. Even the relevant German literature on the subject was hardly known. For example, Féraud, reporting on a visit of his to Germany, was asked about the manurial value of the anaerobic sludge. Féraud said it was excellent, but when pressed for further details, he could not find anything to say to support his opinion.

The interest, however, did not die. The Suez crisis was a welcome opportunity to stress again the National Cause of being Self-Sufficient in Energy. Mainly because of this, the Ministry of Agriculture decided that a mission should go to Germany to investigate the prospects of anaerobic digestion thoroughly. The mission was carried out in 1958 and came back with no very optimistic conclusions (F45): Anaerobic digestion was only relevant in connection with manure economy on a large farm. Only in rare circumstances was production and collection of methane gas sensible; compression of gas was uneconomic under all circumstances. Féraud (F49,50) was not convinced, but by then nobody was interested in his opinions anymore.

Perhaps the history of anaerobic digestion in France is best summarized in an English publication of 1958 (K14): "The information available from France is of a general nature only. No precise details of any single successful installation have been secured."

3.2 West Germany

There are important differences in the development of the interest in biogas digesters between France and Germany. In France, a large number of small digesters had been installed by farmers, but the interest from research institutes and the government was negligible and hardly any scientific publications appeared. On the contrary, in Germany, there was considerable academic interest in the subject and of the 50 or so digesters actually installed, these were backed up by academics or rich, progressive land owners.

Although there had been reports on the production of biogas in France in the later part of the war (G1), this was not taken up at once. However, from 1945 onwards, various people became interested in the subject (G2-5) and the possibility of using anaerobic digestion of agricultural wastes was discussed at great length at an Agricultural Symposium ("KTL-Tagung") in Ludwigs-burg in May 1947. At first, Imhoff and Pöpel, well known from their work on sewage treatment, were most active in pointing out possibilities (G4-6). But it soon turned out that the experience with sewage sludge digesters was of little relevance when treating agricultural wastes (see texts to Figs. 3.9 and 3.10).

Parallel to the interest in digesting agricultural wastes, in particular manure, there was considerable concern about digesting refuse and garbage, and also industrial wastes. (These developments will not be reviewed here.) In all cases, the interest was stimulated mainly by the fuel problems of what is now West-Germany in, and after, the war. In the immediate post-war years, the fact that Germany was not allowed to do "war-relevant" research, for example, research on synthetic petrol, most probably had the effect of stimulating research interest in this area. As far as digestion of manure was concerned, from the beginning the humus value of the resulting manure was stressed as

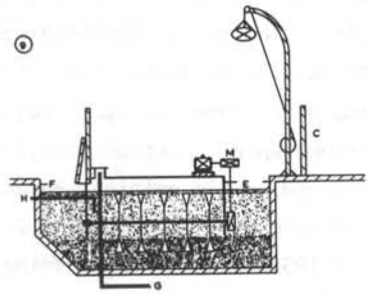


FIG. 3.9. The small-scale digester, type "Darmstadt". The picture (from K15), gives the second design installed in 1954 on the farm of Bertaloth in Rohrbach (near Darmstadt). Most pictures of the "Darmstadt" type in the literature contain elements of the first design, which was already installed by Bertaloth and Reinhold in 1947, but never worked satisfactorily. Manure and other wastes are fed into the digester directly from the stable and extra water is added. The first design followed a suggestion from Imhoff (G16), but it appeared that the stirring mechanism, consisting of large elliptical discs (see pictures in G16, M8) did not work. The stirrer depicted in the above picture is driven by an electromotor for 5-10 minutes twice a day at one rev./min. It breaks the scum layer and adds to the longitudinal transport of the solids. The residence time of the feed is in the order of 2-30 days, on average 15 days. The spent slurry is put on a compost heap by means of a crane. The efflu nt chamber has an overflow (not shown in the picture) which leads to a liquid manure pit. The liquid manure can be recirculated or applied directly to the land. Originally, no heating was provided. After several failures, a reasonable insulation was provided using polystyrene layers in the (subsoil) walls and the cover. However, gas production in winter was still extremely low. Therefore, the digester was later equipped with the means to add warm water or vapour to the digester contents (H). The ditch is 6 m long and 2 m wide and made from concrete. The major part of the feed is the dung of 10-12 large animals. Gas production has been reported to fluctuate between 2 and 13 m^3/day (G45, K15), depending on temperature and other variables of operation. In total, perhaps ten of this type of digester have been built in Germany and Austria, varying in length between 5 and 17 m (C31, G41). None of these has been really successful, due to bad heat economy, problems with the stirrer, and labour-intensive handling (G45, K15).

much as the possibility of obtaining energy.

That the interest in Germany in anaerobic digesters was basically an academic or institutional concern, is shown most clearly by the fact that almost all publications and designs can be grouped under one of the eight German institutes that developed an interest in the subject. In Table 3.2, these institutes, with their interests and names of the people working there are listed. The research on fertilizer and humus value of digested sludge at Göttingen and Völkenrode is discussed in chapter 5. The research on the kinetics of digestion of various materials is discussed in sections 4.1 and 4.2. The general aspects of the economic studies carried out in Frankfurt are discussed in chapter 6.

The characteristics of the reactor designs that have been described in some

TABLE 3.2 Institutes in West Germany that showed an active interest in anaerobic digestion.

place	name of institute	names of people involved	major interest	T, Table F, Figure	References
Berlin	Technical University	Gärtner, Ikonomoff	design	F3.16	G38
Darmstadt	Technical University	Reinhold, Noack	design, digestibility	F3.9 F4.2	G8,16,31, 33,42.
Frankfurt	Kuratorium für Technik in der Landwirtschaft	Feldmann, Stauss	economic evaluation	F6.1	G17,25,37, 39,44,45, 47,48
Göttingen	University, Institute for Soil Science and Agricultural Chemistry	Scheffer, Kemmler, and others	manurial quality	T5.2 F5.1	G15,22,23 34,35
Hohenheim	University	Müller, Wick	design		G32,54
München	University/private	Liebmann, Götz, Strell	design, microbiology	F3.12 F3.13 F4.13	G7,18,39, 41,52,A7
Verden	Ferdinand Schmidt Deutsche Futter-konservierungs-Gesellschaft	Schmidt, Eggersglüss	design ("Allerhop")	F3.10 F3.11	G9-13,24, 27-29,53
Völkenrode	Federal Research Institute for Agriculture, Institute for Humus Research	Sauerlandt, Tietjen, and others	manurial quality, comparison of designs	T5.2	G27,30,36, 43,49-51, 55,56,59, 60
Hanover	Technical University	Poetsch	design	F3.14 F3.15	G58

TABLE 3.3 Major characteristics of West German designs. Most of these designs are also incorporated in Table 6.1. All West German designs have some provision for heating the digester contents and attempt to reduce labour costs as far as possible. Today one of the "Darmstadt" and one of the "Allerhop" designs is still in operation.

type	scale	predigestion	feed	agitation	experience	see FIG.	references
"Darmstadt"	small	-	liquid	mechanical	3-5 installed, many problems	3.9	G8,16,45 K15,M8
"Allerhop"	large	-	liquid	pneumatic	about 15 sold (cf. text)	3.10	G9-12,45, K15,M8
"München"	medium	+	solid	none	one pilot plant	3.12	G7,39
"Hohenheim"	medium	+	solid	none	marketed, 0-2 sold (cf. text)		C27
"Berlin"	small	-	liquid	hydraulic	one in operation for many years	3.16	G38,45,M8
"Hannover"	small	+	liquid	hydraulic	one pilot plant	3.14	G58,K15
"Untersontheim"	medium	-	liquid	pneumatic	built by Mr. Weber, many problems		G45,N14

detail in the literature are summarized in Table 3.3. Of these designs, only one, the large-scale "Allerhop"-type, can be said to have surpassed the pilot-plant stage. All designs are more sophisticated than the French one. However, the major design and operation problems were the same as in France: (i) heating and (ii) difficulties in breaking the scum layer. Technical details on a number of designs are given in Figs. 3.9-3.16, together with the major problems in operating the digesters.

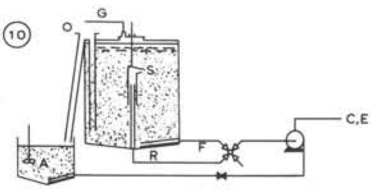
The publications between 1949 and 1956 are mainly concerned with descriptions of the various designs and research on the fertilizer value of the anaerobic sludge. They contain very little information on the actual performance of the digesters in operation. At the "Grüne Woche" in Berlin in 1953, both the "Darmstadt" and the "Allerhop" design were displayed, and many of the 500,000 visitors will have seen them (G19,20). This generated some publicity, but very little interest on the side of the farmers. By 1956, and probably quite some time before, it had been realized that, in terms of energy production, anaerobic digestion would never be economical, and in particular, not on a small scale. Nevertheless, the large number of essays on the subject gathered in the 1956 serial publication edited by Liebmann (G41), was altogether favourable about the prospects of anaerobic digestion, stressing the manurial value and the possible reduction in labour, compared with conventional ways of manure processing. This opinion, however, was based more on a commitment to anaerobic digestion than on straight analysis of the facts. In the years since 1948, none of the designs meant for small- or medium-scale operation (some of which were patented) could refer to any positive experience. Only one of them, the "Hohenheim"-type consisting of a 10 m^3 horizontal cylindrical steel vessel filled with manure was actually marketed (by "Maschinenfabrik Adelsheim GmbH"), but it is not even known whether one has ever been sold. As far as the large-scale "Allerhop"-design was concerned, certainly a large number of "bihugas plants" had been installed (see Table 3.4) and they were all working without serious problems. However, the "Allerhop"-design was basically a new, quite revolutionary way of processing manure in liquid form at minimum labour costs, characterized by the innovation of the process taking place under anaerobic conditions (thus reducing nitrogen losses). Collecting methane was an auxiliary, which was hardly ever economical. By 1959, the system was still sold, but the possibility of methane collection was barely mentioned (G53).

The publication of 1956 just referred to, also ends the R & D interest in anaerobic digestion in West Germany. Although there are a few post-1956 publications presenting new data or designs, they are all based on work carried out earlier. For example, the Poetsch (1963) publication is a report of work that

TABLE 3.4. Large-scale "bihugas" digesters, type "Allerhop", that have been installed on farms in West Germany by the firm "Deutsche Futterkonzervierungs Gesellschaft" (DEFU, Verden). The data given are compiled from (C37, F45, G63, K15). In many cases, the gas production is used completely to drive the powerful central pump and to heat the digester. The digester in Benediktbeuern is still in operation.

	place	owner	number of digesters	digester volume	number of large animals	annual gas production (m^3)
1948	Soltau (Allerhop)	Schmidt	3	160	50	40,000
1952	Hornburg	Lüdeke	4	560	110	135,000
1952	Schlitz	Graf Görtz	3	630	110	50-100,000
1952	Breitenburg	Graf Rantzau	4	840	220	200,000
1953	Plattling	Gräfl. zu P. et al	2	480	125	120,000
1953	Landshut	Gerauer	1	130	25	
1953	Wesselburen	Kahlke	2	280	45	
1954	Weilheim	Thiel	1	220	75	
1954	Weiszweiler	Dr. Leyers	1	180	50	30,000
1954	Benediktbeuern	Monastry	2	480	165	
1955	Bad Driburg	Dr. von Menges	1	96	50	18,000
1957	Hamburg	state farm	4	960	100	300,000
1957	Volmarstein	Wehberg	1	150	50	
1957	Plettenberg	Achenbach	1	104	38	
1957	Ennepe	Lemmert	1	104	30	

(10)



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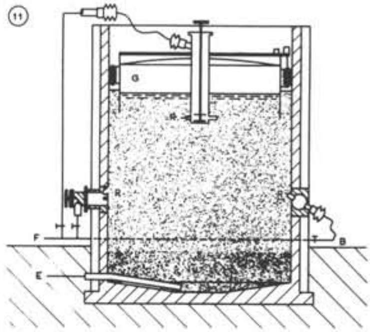
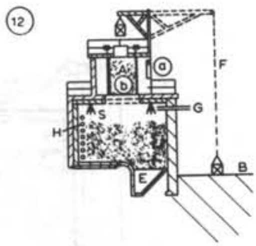


FIG. 3.10. Schematic picture of the "bihugas" plant, type "Allerhop", patented by Schmidt and Eggersglüss in 1949/50 (G9, 10), described in detail in (G24) as well as in numerous East and West European publications. The installation consists of (i) a tank to store and mix the feed, which consists of animal dung and straw (water is added if necessary to reach 15% suspended solids concentration), (ii) one to four digesters, (iii) one to three spent slurry (liquid manure) containers, (iv) a gas holder. The last two are not shown in the picture. The whole system is completely closed, and using the appropriate pipes and valves, one central pump does all the transportation. The animal excreta are flushed from the stables, chopped straw and water is added at some point, and the manure does not come into contact with air until it is taken from the digested slurry container to be put on the fields. From the mixing tank (a) feed is pumped into the bottom of the digester once a day. The first design, put into operation at Schmidt's experimental farm "Allerhop", was equipped with conventional stirrers (again on the advice of Pöpel) which, however, could not break the scum layer. The major innovation that Schmidt and Eggersglüss introduced, was a powerful rotating jet, which can be raised and lowered by means of a telescopic pipe, through the range in which the crust forms. This proved to be successful. In the 1950 patent (G10), five different detailed designs are presented as to how to break the scum layer from below, using a liquid jet. The jet is operated by the same pump mentioned above, about three times a day for 10-15 minutes, liquid being drawn from the bottom of the digester. The jet is also used to transfer slurry from the digester to the storage chambers (every two or three weeks). Before transferring the liquid manure, the digester contents are thoroughly mixed. The contents of the digester are kept at 30°C by circulating the slurry through a heat exchanger, or by direct injection of steam into the digester. The digesters are upright cylinders from reinforced concrete and thermally insulated.

FIG. 3.11. Bihugas digester, type "Allerhop II", for medium-scale application as patented by Schmidt and Eggersglüss in Canada in 1954 (G27). As the authors note in the patent, the prime motive for the design is the production of good quality synthetic manure with minimum labour costs (rather than gas). It is assumed that the digester will not, in general, be heated. The gas holder (G) which is combined with the digester, has only a limited capacity and has the status of an auxiliary. As in the German patents, the innovation is contained in the use of the special liquid jets, the design depicted being equipped with one moving and two fixed nozzles (R). As far as is known, digesters according to this design have never been installed.



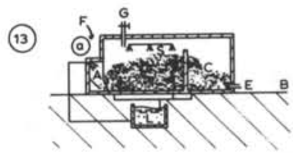
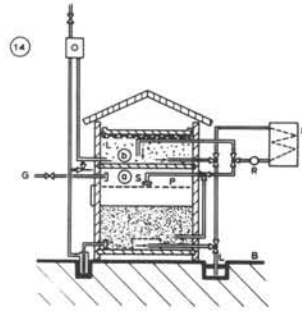


FIG. 3.12. Digester for solid manure, type "München I", as patented by Strell, Liebmann and Götz in 1948 (G7). The installation consists of an aerobic predigester (A) on top of the actual digester, and a separate gas holder. It is operated semi-continuously; every six days manure being transferred from the predigester to the digester by opening a hatch (b). The predigester is filled from the top and equipped with shutters for air circulation (a). The digester is made of metal, placed in a concrete house, with insulation in between. It is equipped with hot water pipes for heating and sprinklers (S) which are used to add a yeast solution containing hormones ("plasmolysat"), which is said to increase the activity of the anaerobic microbes. The digester is emptied at the bottom by mechanical means (E). The residence time is prescribed as 30 days. Apparently, one such digester has been installed on an experimental basis at the state farm "Grub" by Götz (G39), but performance data have never been reported. Götz says in 1956 (G39) that from all the German and foreign designs, this is the only one that is using solid manure. However, both in France (F23, see Fig. 3.3) and in Switzerland (K31), similar designs have been patented.

FIG. 3.13. Digester for solid manure, type "München II". In order to reduce the labour requirements for a system handling solid manure, Götz (G35) has proposed an adaptation of the "München I" design, in which the solid manure is periodically transferred from predigester (A) to digester (U) to compost storage (C) using liquid (manure) which is pumped into A, using the nozzle (a). After this operation has been carried out (every six days), the liquid is allowed to drain in a (subsoil) container, where it stays until the next time. As far as is known, this design has never been tried out in practice.

was in fact carried out between 1953 and 1956. The publications of Barth in 1963, 1964 and 1965 are similar in style to the post-1956 publications in France. For example, in 1963, he wrote that it was true that the "Darmstadt"-digester on Bertaloth's farm was no longer working, and neither was the digester of Weber, but from that it did not follow that building a digester would not be an attractive enterprise. (Because, apparently nobody was convinced by this argument, Barth wrote in 1965 that a digester on the farm of the farmer Bertaloth, by then 20 years old, was still working satisfactorily.) The 1969 handbook (G63) spends only a few pages of descriptive text on anaerobic digestion based on the 1956 essays. At that time, five "Allerhop"-bihugas plants were still in operation, and presumably not more than a couple of the small-scale digesters.



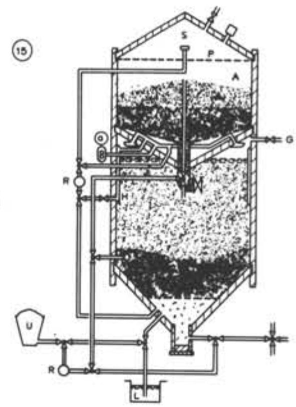


FIG. 3.14. Wooden medium-scale digester, type "Hannover", designed by Poetsch (G58). Digester and gas holder are combined in one wooden structure. Timber is chosen as construction material because of its better insulation properties. When the gas production increases the pressure in (a), liquid manure is transferred via 0 to (b), which has a floating cover. Liquid manure can be recirculated using the pump R, to heat it (H) or to spray it over the manure (S) by means of a perforated plate (P). Note that this design is basically a sophisticated "Algeria" design (Figs. 3.1, 3.7, and 3.8). Loading and unloading is by hand and therefore highly labour intensive. The design is considerably cheaper than any conventional one with a separate gas holder. However, if only one installation is used, there is no gas available during (un) loading as well as some days after. Because of insurmountable problems with the maintenance of satisfactory seals between the planks, the design never passed into production.

FIG. 3.15. Wooden design for use in the tropics, type "Hannover II", reproduced here only for reasons of curiosity. The design combines ideas of the "Hannover"-type given in the previous figure and the "München"-design (see Fig. 3.12). The aerobic predigester is aerated via (a). Further details in (G58). A prototype of this design has never been built.

3.3 Other countries in Western Europe

3.3.1 General. On the basis of the temperature-dependence of anaerobic digestion, one may expect a greater interest in countries where the average ambient temperature is higher. There is no support for this. Apart from France and West Germany (already discussed), interest has developed in Italy, Spain, Belgium and England. These developments are discussed below. As far as can be ascertained, the developments in Norway, Sweden, and The Netherlands have gone unnoticed. At one time, in Finland, the "Allerhop"-bihugas plant received some attention as a possible way of manure processing (K41), but no further interests ensued. Information of marginal interest in other Western European countries is as follows:

(a) Denmark. Influenced by the German literature, at least three digesters

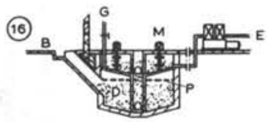


FIG. 3.16. Digester with fixed gas container, type "Berlin" (G38). The idea behind this design stems from the "Boufarik" type (see Fig. 3.8). Digester, gas holder, and spent-sludge container are part of one building structure, without any moving parts except for the stirrers (M) in the spent sludge storage chamber. The digester is loaded with solid and liquid manure directly from the barn (F). When the gas pressure rises in D, liquid is transferred from D to C. If more gas is used, then the used liquid flows back from C to D. Hence, the sludge level in D moves periodically up and down through a grid provided at the right height. This grid should break up the scum layer. It is assumed that digested sludge will sink to the bottom and be transferred to C sooner or later. The digester has been designed at the Technical University of Berlin and a prototype of 5-6 m diameter and 3.5 m high has been working satisfactorily for at least a brief time at a farm in the Tyrol (G45). However, the farmer uses the waste of a cotton spinning mill (instead of straw) which is better to deal with than conventional manure. No information is available as to how long the plant has, in fact been in operation. The installation of a second digester of this type in Bavaria was not completed, because the principal designer, Ikonomoff, died.

were installed in about 1952 (M5). Two of them never worked. One, in Vaalse (Falster), working on the principles of the "Allerhop"-design (see Fig. 3.10) was in operation for about three years, but not wholly satisfactory. In general, the opinion seemed to be that investment costs were too high to consider it as a suitable manure processing system.

(b) Austria. A few small-scale digesters of the "Darmstadt"-design were installed, which have proved to be unsuccessful (G45, K14). Reference has already been made to the successful operation for many years of a "Berlin"-design on a farm in Tirol. Given the specific feed available (see text to Fig. 3.16), this is not of general significance. No publications dealing specifically with the experience in Austria have been located.

(c) Switzerland. In 1943, Jonneret (K31) took out a patent concerning a digester for solid manure. The design is in many respects similar (but slightly more sophisticated) to the one that was patented much later by Massaux in France (F23). It is not known on what experience this design was based, but one can speculate that Jonneret was aware of the publications of Ducellier and Isman, as well as early American publications (see section 3.5). Certainly, not very many digesters of this design have been installed. In a publication of 1959 (K32) it appears that the Swiss State Agricultural Research Institute ("Eidg. Agrikulturchemischen Versuchsanstalt", Bern) had been following developments abroad. The evaluation was that (i) R & D interest in Germany was only possible because of Marshall-Aid, (ii) given the size of farms and the way of keeping animals, anaerobic digestion was even less economical for Switzerland than for Germany.

3.3.2 Italy. Interest in anaerobic digestion seems to have emerged in Italy as early as 1910, when methane was collected on a farm in Fogliano and used, inter alia, to run a 3 hp motor (H17). This was taken up by the director of a large vocational school in this region, and experiments were carried out for quite some time. However, the results were not such that the subject gained wider interest.

During World War II, the possibility of obtaining energy from local sources, such as methane from organic waste, was widely discussed. It may be speculated that the specific interest in methane production was stimulated by the Italian translation of Imhoff's book, as well as a similar book in Italian by Friedmann (H11), in which the general principles of sewage sludge were discussed, and the possibility of using other inputs for the digester were stressed. All early Italian publications (H11-17) indicate that the work of Buswell (L7) in the USA was known. The design patented by the farmer Castoldi in 1941 of a 65 m^3 digester is most certainly an adaptation from a conventional sewage sludge digester (H12). At the "Methane Convention" in Bologna in May 1940, Roberti reported on preliminary experiments with his 70 m^3 digester. Experimental work was also carried out at the "Stazione Sperimentale dell'Ente Autonomo Acquedatto Pugliese" at Foggia (H17). Tomnasi reported experiments with manure obtained after anaerobic processing (H18). Although the potentials were discussed extensively, due to practical and economic problems, virtually no digesters were installed during the war (H17).

After the war, the development in Italy quickly changed its orientation from Germany to France. That is to say, contact was not lost with the German literature, but all results in practice, were similar to those in France. Although no direct information could be acquired, one may guess that most digesters in Italy were installed between 1950 and 1955. In a publication of 1957 (H20), in total, twelve digesters are quoted ranging in sizes from 12 to 72 m^3, almost all of them at institutions (schools, universities, monasteries). From this it may be concluded that the number of digesters that have actually been installed on "normal" farms will not have been very large.

All digesters that have been built in Italy seem to have been of the basic "Algeria"- or "Paris"-type (see Figs. 3.1-3.2). The larger installations were equipped with cranes for loading and unloading. Since 1951, the firm "Biogas" in Turin has been selling digesters under the license of Massaux (Fig. 3.3). About 40 digesters have been sold (one to the Institute of Humic Research in Völkenrode, cf. section 5.1). A number of digesters were also installed by the firm "Pergas" in Turin. (A photograph of a group of eight 12 m^3 digesters with a crane constructed by "Pergas" is given in H20.)

At the Universities of both Turin and Milan, research has been carried out on the subject: in Turin, mainly on the fertilizer value (the results being similar to those at Völkenrode, see section 5.3); in Milan, Danadeo wrote his Ph.D. thesis on experiments with the eight "Pergas" digesters referred to above (G45).

After 1958, the interest in anaerobic digestion for application on the farm disappeared, which is comparable to the developments in France and Germany. The two post- 1958 publications in the bibliography are concerned with the possibility of using anaerobic digestion for the wastes of cheese and poultry factories.

3.3.3 Spain. Here the interest in methane production developed much later than in Italy and France (in fact only after most digesters had been installed there). In 1955, it was suggested on the basis of a rough economic analysis, that the Ministry of Agriculture should finance some pilot plants (H31). By 1956, experimental research had already started at the National Agricultural Research Institute ("Instituto Nacional de Investigaciones Agronómicos", Madrid) and in 1960 a report was available (H33). Batch 10 m^3 digesters of French design were used. Up till 1965, the potentials of applying anaerobic digestion on the farm were stressed in view of rural development. However, no positive evidence is available that a digester has actually been in operation on a normal farm.

3.3.4 Belgium. Following the development in France, by 1942, work on anaerobic digestion started at the State Agricultural Institute ("Institut Agronomique de l'Etat", Gembloux). By 1952, three groups of digesters (30-75 m^3) were in operation (H4). In the years 1949-1952, much publicity was given to the subject, stressing the potential increase of comfort on the farm, together with the possibility of obtaining good quality fertilizer. The French literature on the subject had been carefully studied, and various suggestions were made to improve the design, in particular, aspects of the heat economy. The most fully worked out design is given in Fig. 3.17.

Although it is sometimes stated that "many" (G17) digesters have been in operation in Belgium, there is only positive evidence for one, which started operation in 1951 at Péronnes-les-Binche (Henegouwen). The installation con-

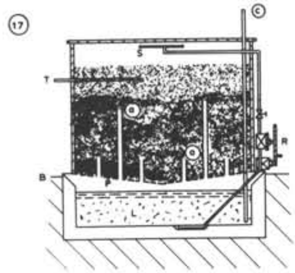


FIG. 3.17. Digester patented in Belgium by Milquet (H3), type "Brussels". Like the French digesters, loading and unloading is manual and there is an aerobic predigestion to heat the contents. By building the whole structure underground or in a shed and using double metal walls with low-density cellular concrete between them, and putting a thick cork layer on the cover, it is claimed that without heating, it can be kept at 40°C for six weeks, unless there is severe frost. The solid manure is resting on a perforated plate (P). The tubes (a) connected to shutters, serve aeration during predigestion. Using the hand pump R, liquid manure (L) can be sprayed (S) over the manure. The total weight of liquid in the reservoir is three times the weight of the manure. During digestion, the manure is saturated with 50-75% (weight) of water. To regulate the air shutters and the pump, the digester is equipped with a thermometer (T) and a liquid gauging-rod (c). As far as is known, a digester according to this design has never been built.

sisted of two 10 m³ digesters heated with manure according to the thermosiphon principle (cf. text to Fig. 3.5) and seems to have been in operation for some time (H1).

In a publication of 1961 (H5) from the State Agricultural Institute mentioned above, no reference is made to the experimental work carried out at the Institute, whereas it is concluded that anaerobic digestion, although interesting, is not economically feasible in Belgium.

3.3.5 England. Lord Iveagh, having a large estate at Pyrford Court (Surrey) became interested in methane digestion as a result of work on manure by Richards at Rothamsted (cf. section 2.3.1). After various try-outs with the help of the Rothamsted staff, a definitive digester was installed in 1929 (K14). The 300 m³ digester worked basically on straw, but was topped every six months with 16 loads of manure. Gas production fluctuated between 12 and 120 m³ per day (K3). The methane was used for cooking and lighting on the estate. Accurate records of its performance were kept for 20 years, but they were unfortunately destroyed by a fire, just before any national interest in the subject emerged. It ceased operation in 1960. From the fact that no other estates ever considered installing a digester, together with the lack of any publications from Rothamsted on the matter, it may be concluded that Lord Iveagh's large-scale digester, although working, was not economical.

After some news items based on information from Germany (published under the title "Some Curiosities of Mechanization"), the subject gained wide interest due to a paper read by Rosenberg (K8) at an Open Meeting of the Institution of British Agricultural Engineers in London, in November 1951. Rosenberg's knowledge was based on the articles of Hisserich (G3) and a personal visit to Germany, in particular to Allerhop. The tone of the paper was not excessively optimistic, but he argued that with some development work, the production of methane gas from farm wastes might replace the imported fuel for the quarter million of tractors used in England and Wales. Few people took this suggestion very seriously (K6, P3), but nevertheless, the paper subsequently had a great impact, as many publications appeared afterwards in Britain and the Commonwealth, which gave an optimistic view of the potentialities of anaerobic digestion, in particular for the (sub-) tropics (see section 3.7).

In 1954, a small-scale digester started operation on a farm in Gloucestershire owned by J. Stanworth. The installation consisted of three small digesters and a gas holder, according to the French system, and was designed and financed by D. Tollemache who had been inspired by the publications of Martin-Leake (K7, P3-5), who had himself derived his knowledge from Rosenberg, and the book of Mignotte (F33). Tollemache actually went to France to investigate the

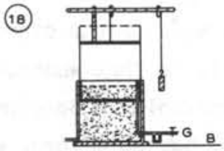


FIG. 3.18. Demonstration model of digester with gas holder staged by British Organic Products Ltd. at the Dublin Spring Show in 1954 (K10). The design is derived from the basic "Algeria"-type (see Fig. 3.1). The gas holder can be removed, as indicated, to facilitate (un)loading. The advised digestion time is 90 days. As far as is known, the number of plants sold is zero.

matter. There have been innumerable references in the literature to this "digester in Gloucestershire". It may be stressed however, that after three months of operation, in the summer of 1954, it stopped and never worked again.

Also in 1954, British Organic Products, a firm already active in apparatus for municipal waste treatment (K13), presented a small-scale design at the "Dublin Spring Show" (K10) - see Fig. 3.18. Two other firms are known to have shown interest in the subject, but soon lost it again through lack of any response (K14). At the most, only a few of these designs will have been sold, as the total number of digesters installed in Britain at that time is most probably less than 10. All reports on existing plants refer to problems, resulting in minimal or no gas production (K14).

Because of the numerous requests for information received by official institutes, an evaluatory report has twice been prepared. First, in 1958, by representatives of the Rothamsted Experimental Station, the National Agricultural Advisory Service and the Agricultural Land Service (K14). In this it was concluded that the process was basically sound, but not economical, except perhaps for application overseas or in connection with greenhouses. (The latter suggestion was not taken up anywhere.)

Secondly, in 1961, a visit was made to Germany by H.J. Nation, on behalf of the National Institute of Agricultural Engineering. A detailed report was prepared on the basis of this visit and it was concluded that "plants of any type for the production of methane from farmyard manure cannot be justified economically where other sources of power are available" (K15).

3.4 Eastern Europe

3.4.1 General. A priori, one might speculate that before the second World War, interest in anaerobic digestion of agricultural waste might have developed in the USSR, because many large collective and state farms ("kolkhoz" and "sovkhoz") were established, usually in very remote areas and with a strong emphasis on self-sufficiency. There is no evidence that this happened. In Russian publications appearing between 1956 and 1958, reference is made to the first anaerobic digesters being installed at kolkhoz's in 1948. No references earlier than 1956 have been found.

From the Eastern European publications reviewed here, it is clear that the interest in anaerobic digestion that appears from these publications stems from the development in Western Europe, in particular West Germany. From the references given, and the general knowledge of anaerobic digestion that is reviewed in the Eastern European publications, it is clear that the subject was first taken up in East Germany in about 1953. About three years later, the matter was extended to Czechoslovakia, Poland, the USSR, and Hungary on the basis of East German publications, in particular a small book on "biogas" by Poch (M3) published in 1953. (Compare also the dates of the various Eastern

European publications given in the bibliography.)

The developments in the five Eastern European countries just mentioned will be summarized in the next subsections. Developments in Bulgaria have been marginal (M75). No references have been found to any significant interest in anaerobic digestion in Yugoslavia or Roumania.

3.4.2 East Germany (M1-11). No digesters have been installed in a real working situation in East Germany. However, a significant amount of work was carried out to find out whether - in view of the developments in West Germany - anaerobic digestion was of relevance to the future of East German agriculture. As there are mainly only large state farms in East Germany, the interest was concentrated on medium- and large-scale digesters.

Three institutes have been engaged in work on anaerobic digestion. At Halle, Schmalfuss and Fiedler carried out field experiments with manure treated anaerobically (C24). Some details of the results have been published (M11), but as there are no references to it in East European publications (while there are references to similar work carried out in West Germany), it may be assumed that this work was of little importance.

General interest was first stimulated by the influential Professor Kertscher of the University in Jena (M2). Some work was carried out there, in

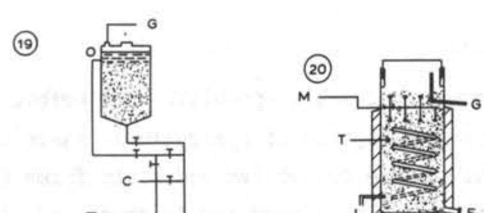


FIG. 3.19 Schematic picture of the digesters used at the Technical University of Dresden, following the principle of the "Allerhop"-design (cf. Fig. 3.10). Special provisions are necessary to ensure the reliability of the overflow (O), as this is easily blocked. Three digesters according to the "Allerhop"-type were build, one of 150 m^3 with hydrodynamic breaking of the scum layer with the nozzles designed by Schmidt-Eggersglüss (G10), one of 50 m^3 which uses compressed gas to break the scum layer (from below), and one of 30 m^3 where there are provisions to induce pressure fluctuations in the digester vessel. It was found that not one of these methods was better than any of the other two (M7).

FIG. 3.20 One of the small-scale digesters (3-10 m^3) that has been in use in Skierniewicach (Poland) from 1956 to 1960 (M64). It is basically similar to the simple French digesters, but provided with a hand stirrer (M) to break the scum layer, and a provision to heat the contents via hot water tubes (H). It seems that there were no important operational problems, but the heat balance over the digester prevented economic application.

particular by Poch, who wrote his Ph.D. thesis on the subject. They concentrated on anaerobic digestion of manure in the thermophilic region (about 50°C), because at that temperature the hygienic properties of the manure are much better. Although more heating is necessary, digestion is quicker (cf. section 4.2), hence the extra heating costs may be compensated by lower investment costs. As far as is known, this is the only work ever carried out on manure digestion at higher temperatures (in the period under review). As is apparent from a publication of 1968 (E8), and also from recent reviews (E9), with hygienic standards becoming more stringent, the potential of anaerobic digestion of manure at 50°C may well have been undervalued until now.

In terms of volume and of quality, most work was carried out at the Technical University of Dresden by Rosegger and Neuling in a brief period, 1954-1956 (M5-10). They compared three modifications of the "Allerhop"-design. Some details of this are given in the text to Fig. 3.19. Further, Rosegger and Neuling were the only researchers (in the period under review) who realized fully the consequences of the fact that the cost of the gas holder takes up to 50% of the investment costs of a digester, and they analysed in detail possibilities to introduce cost-reducing innovations. The conventional gas storage techniques were reviewed, and it was concluded that they were inherently expensive (M6). Development work started on a gas storage system consisting of a gas sack made of cotton and rubber in which the pressure was kept more or less constant by hanging it from a roof using counter-weights. Because by 1957 it was concluded that biogas plants cannot be recommended as economic (even in countries having large agricultural units, such as the socialistic states), this work was not continued. [Probably independently, the idea of "rubber-bag digesters" was re-invented in South East Asia after 1970 (Q5).]

3.4.3 Czechoslovakia (M71-72). It is reported that in 1955, a 100 m^3 digester was in operation in Levocskych Lúkach, producing 80-100 m^3 gas per day (M71). It is not known how long it had been in operation. Suggestions were made to mechanize and scale-up the "Algeria"-design, taking advantage of pre-digestion, by slowly moving small carts containing manure through an insulated closed tunnel kept under anaerobic conditions (M5). As far as is known, this was not tried out in practice. There was close contact between Rosegger in Dresden and the people in Czechoslovakia interested in the subject. No post-1956 Czech publications on the subject are known.

3.4.4 Poland (M61-65). Interest in Poland started around 1955. Compared with East Germany and Czechoslovakia, where methane (energy recovery) played a role at least as important as manure processing aspects, the main motivation to engage in R & D in Poland was stimulated by the alleged possibilities of eliminating nitrogen losses during manure processing. From the first general publications in 1956 and 1957, it is clear that both the French and the German literature on the subject had been thoroughly studied. Experimental work was carried out between 1956 and 1960 in pilot-plant and full scale digesters in Skierniewicach (near Warsaw). The design used at 3 and 10 m^3 scale is given in Fig. 3.20. Results on the kinetics of digestion of manure at different temperatures and solid concentrations is discussed in the next chapter (see in particular Figs. 4.6 and 4.9). Work on manure qualities is discussed in chapter 5.

3.4.5 *USSR* (M21-30). In the first Russian publication of 1956, the foreign literature on the subject was reviewed. Most probably, this review is based on the small book of Poch (1953, M3). The author, Romashkevich, was working at the All-Union Research Institute of Fertilizers and Agronomic Soil Science in Moscow. His later publications (M29, 30) deal solely with laboratory work concerned with producing fertilizers from wastes, and not with the actual use of anaerobic digesters on farms. The latter possibility was mainly advocated by Ananiashvili working at a local research branch in Tbilisi (Georgian Republic). Apparently, a digester had already been in operation in the Georgian SSR since 1948 at the kolkhoz "Makharadze". Quite some research must have been carried out by Ananiashvili, the results of which are only available in summarized form in the accessible literature. Some of it is referred to in the next chapter (see in particular Figs. 4.6 and 4.12). A schematic picture of the digester and auxiliaries used by Ananiashvili is given in (M23). It is most probably a design adapted from one of the designs used in Dresden (Fig. 3.19).

In publications of 1957, reference is made to, and photographs are given of, an experimental installation, producing 1000 m^3 gas per day, at the sovkhoz "Pakhomovo" in Tulskoi (also in M28). This digester design is very similar to the "Allerhop" or "Dresden" design. Thirty to sixty per cent of the gas produced is needed for heating digester and gas holder. By 1958, about five large-scale digesters processing manure were in operation in the USSR (M24, 25): two near Moscow, one or two near Tbilisi and one or two others. A design for a large-scale digester was published in (M26); this design was very similar to the conventional design of sewage sludge digesters (cf. Fig. 3.22).

An economic evaluation of 1958 (M25) stated that a minimum of 400 cows would be required. In the publications of 1959 and after, no new developments are mentioned and no reference is made to the performance of digesters in actual operation. It may, therefore, be concluded that anaerobic digestion, even on the largest state farms, was not considered economical.

3.4.6 Hungary (M41-49). In 1956, a note was presented to the Academy of Agricultural Science in France, reporting on the building of eight 70 m^3 digesters at the Institute of Heat Transfer in Budapest, starting operation in the Spring of 1956 (M41). The digesters were designed according to the French philosophy of aerobic predigestion and no heating. It may be speculated that this work was interrupted by the political and military upheaval in Hungary of 1956 (because in the Hungarian publications on the subject, which started to appear in 1958, no reference is made to this work, nor is there any direct confirmation that these digesters have ever been used in further work).

In about 1958, work on anaerobic digestion started in, at least, three Hungarian institutes. At the Agricultural University, Szekeres announced a programme studying not less than eleven different aspects of the fertilizer value of manure digested anaerobically. Imre, who wrote a Ph.D. thesis on the subject referred to in (M49), presumably worked there. However, in his 1965 publication, there is no reference to substantial experimental research data gathered at the Agricultural University, nor have any other experimental papers from this University been found in the literature.

At the Research Institute for Soil Science and Agro-chemistry of the Hungarian Academy of Sciences, Manninger carried out laboratory work on the optimal conditions for digesting swine manure. The results of this are summarized in (M48). There are other brief references in the Hungarian literature showing that there was a particular interest in swine manure. (It was assumed - or experience had shown - that swine manure was more difficult to digest than cow manure.)

Technical-economical evaluations were made at the State Design Office of Civil Engineering in Budapest by a group headed by Bartha (M42). Probably coincidentally, in 1959, contact was made with Indian authorities concerned with large-scale agricultural waste processing (for example at sugar factories), from which ensued various missions of Hungarian specialists to India (N34). This is further discussed in section 3.6 on India.

There are no indications that an anaerobic digester has ever been working in Hungary in an actual setting.

3.5 United States of America

In the USA, there has never been an interest in either small-scale digesters, or the fertilizer and humus value of the residues of anaerobic digestion of agricultural wastes. The developments in the USA are reviewed because of the work carried out on the digestive properties of cellulosic materials, the results of which are relevant for small-scale anaerobic digestion as far as vegetative wastes are used as (part of the) substrate. This is so, even though the motivation for this research was derived from (i) the potential of the large quantities of cellulosic wastes as an energy source (cf. section 2.4.2); (ii) from an interest in the most effective way of dealing with industrial wastes of this type; and (iii) from the potentials of the residue as a useful input for the pulp and paper industry.

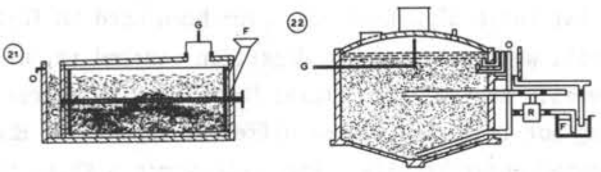


FIG. 3.21 Schematic diagram of the "rotating drum" digester designed by Buswell and Boruff, type "Illinois" (L4). There are clear similarities between this design and the later "Darmstadt"-design (see Fig. 3.9). It is meant principally for digesting fibrous materials which pass more or less in plug-flow through the digester from F to C. The digester itself is a rectangular tank in which a cylindrical wire-covered drum is contained, into which fibrous material is fed. The amount of liquid in the tank can be varied, but it is usually operated completely filled with inoculated water. The cylindrical drum is rotated intermittently to release gas bubbles from the fibrous mass to provide some mixing and to transport the solids longitudinally. In continuous operation, the drum is kept at least half-full to prevent short-circuiting. After some laboratory-scale investigations, two pilot-plant scale digesters of 5 m^3 were built, and for a number of years were operated successfully carrying out experiments with a variety of mainly cellulosic wastes.

FIG. 3.22 Conventional design of a digester, as used at sewage works, adapted for treatment of agricultural wastes. The design given here is taken from a publication of 1963 (L11) for an anaerobic digestion of hog wastes. (It was not actually constructed for that purpose.) Similar designs are already given in the US literature on agricultural waste processing of the 1930s. It is also this type of design that has been used for large-scale digestion of night-soil in India (N22).

Perhaps the institute that has invested the greatest amount of interest in anaerobic digestion, in comparison with any other single institute in the world, was the State Water Survey Division of Illinois, headed by A.M. Buswell, whose numerous publications on the subject cover the period of 1928-1965. The most active period was the first ten years, and the results obtained from 1928-1938 are summarized in (L7). After 1938, no work of relevance for the present review was reported.

The work of Buswell and collaborators falls into three wide categories:

(a) theory of anaerobic digestion and fermentation of pure compounds (this work is not reviewed here); the major results are contained in post-1945 review articles on the theory of anaerobic digestion (A7-13);

(b) digestive properties of numerous waste streams from the food industry (cf. references to Buswell c.s. in Table 2.2 summarizing the data on the digestibility of industrial wastes);

(c) the fermentation of cellulosic materials; the more important results from this category, obtained on a laboratory and pilot-plant scale, are discussed at the appropriate places in the next chapter (see, in particular, tables 4.1-4.7, as well as Fig. 4.11).

The work on the digestibility of cellulosic materials (the main interest always being in cornstalks) started in 1929 (L2). This was very early, and Buswell and collaborators were most probably the first to digest substantial amounts of pure cellulose and more complex substrates. Because, by far most of the work was carried out on a laboratory scale, and none of the fermentation processes they developed was ever put into operation, there has been very little interest in reactor design. Most pilot-plant experiments were carried out in a design, derived directly from the design of a sewage sludge digester (cf. Fig. 3.22). However, one new design was introduced in 1933 (L4) using a rotating drum digester for fibrous materials. Further details of this design are given in Fig. 3.21.

It may be appropriate to quote in full the conclusion Buswell c.s. came to, after ten years of intensive work (L7, p. 185):

> Under the present economic conditions, fuel gas produced by anaerobic fermentation is too expensive to compete with other kinds of fuel, when the raw material must be purchased or transported any distance. As a method of waste disposal, anaerobic digestion is quite economical because of the gas which is produced as a by-product. Under good conditions the process can be made to pay for itself.

Shortly after the research had started in Illinois, the U.S. Department of Agriculture (Bureau of Chemistry and Soils, Agricultural By-Products Laboratory) commissioned research at the Iowa State College to study the digestibility of non-animal agricultural wastes, in particular corn stalks, as a function of temperature, composition and physical form. The main results of this research programme (L8-10) are discussed in the next chapter (see in particular Fig. 4.5 and Table 4.6).

Due to the prevailing economic crisis at the time: "The general problem of utilizing these farm wastes is one of great national economic importance...." (L5). However, by 1939, time had changed, and the interest in anaerobic digestion of agricultural wastes disappeared.

In the early sixties, anaerobic digestion was taken up again at the Iowa State University by Taiganides (L11). But now, the emphasis was on anaerobic digestion of the wastes of large-scale animal farms; and this has been the prime mover for interest in anaerobic digestion in the USA since then. (See on the present "state of the art" section 2.2.4).

3.6 The Indian subcontinent

3.6.1 Prehistory. In section 1.1, reference has already been made to the Matunga Leper Asylum (near Bombay) where, during the period 1895-1920, methane gas was collected. It was collected from septic-tank-type digesters and was used in a gas engine for pumping the sewage, as well as for lighting and cooking purposes (E4). Just after the First World War, research was carried out on the fermentation of cellulose, at the Indian Institute of Science at Bangalore, in order to take advantage of large quantities of potential fuel (banana skins, waste paper, etc.). It was concluded that (large-scale) anaerobic digestion might be a good option for the West Coast of India, which has no coal (D1). As a side interest of the research on potential uses of the water hyacinth, carried out in the 1920s at the University College of Science and Technology in Calcutta, anaerobic digestion was also considered, but after a few preliminary experiments, this line was not pursued (D21). Although these early interests in anaerobic digestion in India were well documented [for example, in a book of Fowler published in 1934 (E4), and based on a series of lectures he had given in India], they had no impact on further developments.

Small-scale anaerobic digestion of cow dung can be traced back to two factors that were instrumental in generating interest in this possibility at the Indian Agriculture Research Institute in New Delhi around 1938. The first was that in the early 1930s, it had been realized that by the standard methods of converting dung and straw to synthetic farmyard manure by aerobic composting, 40-60 per cent of the nitrogen was lost under the prevailing climatic conditions (E6, N1). Because of initial successes with the German "Edelmist" process (cf. section 2.3) at the Indian Institute of Science (E6), a large study was started at the Indian Agricultural Research Institute (IARI) "for the preparation of cheap synthetic manure from town refuse and other waste material" (N1). Although, at that time, gas collection (during anaerobic digestion) was not considered, and the interest was not primarily in the cow dung and other "wastes" of the small farmer, it provided the IARI (in particular in the person of Acharya - who had written a thesis on the subject in

England), with additional knowledge of anaerobic digestion.

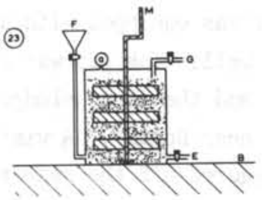
The second factor was the commissioning of the Sewage Purification Station at Dadar (Bombay) in 1937. This plant was equipped with an anaerobic sludge digester, which appeared to work very well. The gas was used for running a five ton lorry for disposing garbage, and the spent sludge (odourless and rich in nitrogen) was sold to farmers near Bombay. A visit of scientists of IARI to this sewage plant in 1938 triggered off the research on small-scale anaerobic digestion of cow dung which began at the IARI in 1939.

3.6.2 The period 1939-1955. Until 1945, activities were restricted to R & D at the IARI. By 1945, a more general interest arose, in particular stimulated by a group at the Poona Agricultural College. In the early fifties, the interest became widespread and a variety of people and organizations were concerned with setting up digesters. The actual number of digesters installed with farmers remained, however, negligible before 1955. The major centres that influenced further development will now be discussed in turn.

Indian Agricultural Research Institute (IARI). Starting with some "bottle"-experiments in 1939, S.V. Desai built the first small-scale digester for cow dung in 1941 (cf. Fig. 3.23). The performance data and other results of laboratory work on anaerobic digestion were published in two papers in 1945 (N2, 4). Some of these data are reviewed in the next chapter (see, in particular, Fig. 4.8). In this research, the emphasis was on obtaining good fertilizer qualities. The gas was only an attractive by-product. However, later developments almost exclusively concentrated on gas collection. Following the two 1945 publications, a widespread interest in the process was evident in India. In the next ten years, the IARI played only a minor role in the further developments.

Poona Agricultural College. N. V. Joshi, former-scientist of IARI, and professor at the Poona Agricultural College (near Bombay) delivered the Presidential Address before the Agricultural Section of the Indian Science Congress in January 1945 (N3). This address, which was devoted to "rural uplift", contained some paragraphs on the potential of anaerobic digestion in using cow dung as a source of both fertilizer and fuel. This address added to the national interest in the subject, and in particular, at Poona, a number of people became seriously involved.

Joshi himself patented a design in 1946 (see Fig. 3.23). Demonstration plants were constructed at a number of places, and a large size commercial plant of his design was constructed at a sugar cane estate in Walchandnagar, processing 2000 kg cow dung per day. Soon after its installation, the digester of the plant cracked due to the gas pressure that could develop due to the



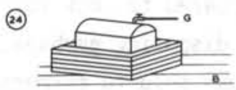


FIG. 3.23 The digester patented by Professor N.V. Joshi in 1946 (as reproduced in Q1), type "Poona". The design consists of a closed oil drum serving as a digester and a separate gas holder. Although it is equipped with a pressure gauge (a), several of Joshi's digesters exploded (because the gas could not escape due to blockage). The design is an adaptation of one of the designs used by Desai at the IARI in the period 1939-1944 (N4). The main differences are: first, Desai used a separate gas holder consisting of an oil drum placed upside down in a slightly larger oil drum partly filled with water: chances of explosion are small in this case. Second, in the Desai design, the feed is introduced at the top. Desai started with a digester without intake and output pipe, but this had the disadvantage that, while recharging every 8-10 days, the anaerobic conditions had to be disturbed. In later designs, the stirrer was left out because no advantage of stirring was found. The oil drums used by Joshi, Desai and others (see for example, pictures of oil drum digesters at the Hirenghatta Farm (West Bengal) in N8) had a volume of 0.2 m^3.

FIG. 3.24 Schematic picture of one of the digesters constructed at the Ramakrishna mission at Belur Math (near Calcutta), photograph in (N8). They tried to minimize the installation costs in order to bring the digester within the economical reach of the poorest farmers. The design depicted here is made from bamboo, earth, and putty (a local cementitious material). Similar construction materials were used by Das Gupta. This approach has only played a marginal role in the anaerobic digester development in India.

formation of a scum layer (foaming) that blocked the exits. Also, one or two of the smaller plants Joshi established, exploded.

At Poona, the effect of various parameters on cow dung digestion was also investigated on a laboratory scale by Narayana and some of it is reviewed in the next chapter.

Sewage works Bombay. At the Sewage Purification Works at Dadar, referred to above, its director Y.N. Kotwal and his assistant, Barkar, carried out work on cow dung with a small experimental digester. One of the things they established was that digestion could be speeded up by adding urine. However, they did not attempt to design a plant to be installed on farms.

Patel Gas Crafters Private Ltd. (Bombay). This firm was established in 1951 by J.J. Patel, who studied at Poona and entered the anaerobic field in 1949 while working with Mapara Parekh & Co. (Santa Cruz, Bombay). Patel's first design, named "Gramlaxmi", differed in a number of ways from previous

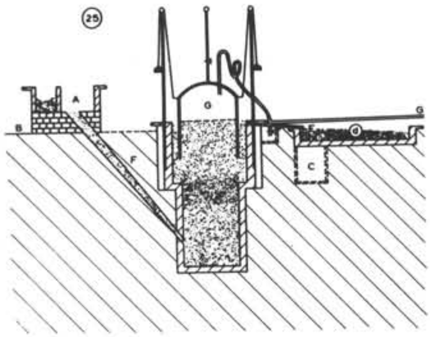


FIG. 3.25 The IARI design that was launched in 1956 (N10), type "Delhi". The digester is constructed underground, using bricks. The gas holder is made from iron. For the other parts, different options are available depending on circumstances. For example, originally, metal posts were used, but later instructions were given to use bamboo posts (N11). The effluent can be fed into either a drying bed (d) or a compost pit, C. It is meant to process about 50 kg cow dung per day (3-4 head cattle), producing 2-3 m^3 gas per day. Because the effluent leaves at the top, there is no reason to have two chambers as in the KVIC design (Fig. 3.27). A systematic comparison of the KVIC and IARI designs has never been reported. Since 1956, no significant innovations have been realized in the IARI-design. In 1959, the possibility of fermenting other farm wastes was also considered. This caused more blocking in the feed and discharge pipe, as well as floating materials in the gas holder. The diameter of the feed pipe was increased to 12.5 cm (N16). In 1964, it was suggested that the spent-sludge could be drained using leaves, thus reclaiming water and having a smaller weight of sludge to be transferred to the soil (N29).

designs (see Fig. 3.26): (i) combination of digester and gas holder in one unit, (ii) built partly underground, (iii) daily, instead of weekly, loadings. The first digester of this type was installed in 1950 at the Faculty of Agriculture of the Osmania University in Hyderabad, and it was exhibited in Hyderabad in 1951 and 1953. By 1953, perhaps five of these plants had been sold. Taking advantage of the experience with this design and of reports on the performance of digesters designed by others, Patel produced early in 1954, his "definitive" design (see Fig. 3.27). Basically, it is this digester design that has been installed in India in later years (see below).

Other activities in West Bengal. In 1953, attempts were made at the West Bengal Government Farm in Hirenghetta to construct a digester and gas holder solely from oil drums (see photographs in N8). As there are no later references to this in the literature, presumably they were not successful in some way. Between 1952 and 1954, a rather influential role was played by S. Ch. Das Gupta of the Khadi Pratisthan at Sodepur (near Calcutta). His interest was

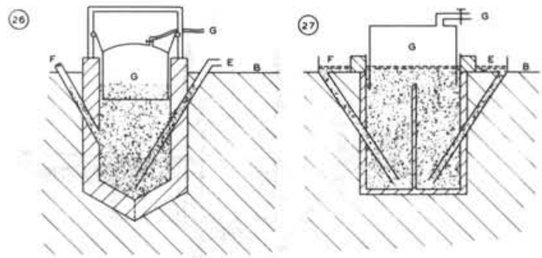


FIG. 3.26 The original "Gramlaxmi" biogas plant designed by Patel in 1950 (N7). Digester and gas holder are combined in one, which gives a less reliable control of gas pressure than with a separate gas holder, but is much cheaper. It is also possible to rotate the gas holder over some distance, which provides some mixing in the interior of the digester. It is operated semi-continuously, adding feed every day. (Until then, it was common in India to load digesters every 7-10 days.) Daily feeding gives less chances of scum layer and fixed sediments formation.

FIG. 3.27 The improved "Gramlaxmi" design which has two chambers, type "Bombay", designed by Patel in 1953/54. Compared with earlier designs, improvements includes: (i) no cement plaster on the brick walls so that the bricks could freely absorb liquid, which made them gas proof; (ii) a more sophisticated construction of the gas holder with poles at various distances from the centre to the periphery (not shown in the figure) so that half a turn of the gas holder would disturb any matt (dry scum layer) that might have formed on the surface. It is this design that was incorporated in the rural development schemes of the Khadi and Village Industry Commission from 1962 onwards (Q9). The main function of the central overflow is to prevent short-circuiting between inlet and outlet. It would be interesting to know a residence time distribution of cow dung added daily to the digester, but such data are not available.

in reducing costs for the small farmer. For this reason, he experimented with digesters made out of bamboo-thatch cylinders sunk into the ground. He also tried to make gas holders of bamboo-thatch plastered with earth and putty (an indigeneous cementitious material). Similar activities were going on at the Ramakrishna Mission at Belur Math (near Bombay), in particular in the person of S. Vishwakarmanand. A schematic picture of the digesters advocated by Das Gupta and Vishwakarmanand is given in Fig. 3.24. The attempts of Das Gupta and others to use bamboo were not successful: even if leaking problems could be overcome, rats or other small animals, or insects would destroy the bamboo. Das Gupta suggested numerous small innovations in the construction and operation of the digesters. Some of these, for example using an overflow instead of a slurry removal pipe, were taken over in some of the later designs. Others, such as the suggestion of keeping a negative pressure in the gas holder when no gas is used, were assessed to be disadvantageous. (A negative pressure increases the risk of explosions due to air leakage into the gas holder.)

Miscellaneous activities. In the period 1945-1955, numerous other individuals in India were engaged in anaerobic digesters in one way or another. It would ask for a detailed study of the contents of local periodicals to obtain a reasonably complete picture of what actually took place.

It is of interest to note that in the Indian literature, no reference is made to the digesters that were in operation between 1944 and 1949 on an estate owned by a Frenchman, M. Renaudot. In the French literature (F13, 17, N5), details are given of its performance. Average gas production was 15-25 m^3 per day. The gas was also compressed, and for at least three years, used for running tractors.

3.6.3 The period 1955-1959. Before 1955, few digesters had been installed on a (semi-) commercial basis. By about 1955, the official interest in the subject increased suddenly, and about 500 plants were installed with government support, all of which were abandoned in due course. Although the literature is rather confused on this point, it seems that most of these 500 digesters installed were of the IARI-design depicted in Fig. 3.25. This design was first published by IARI in 1956 (N10-11). It is basically the design patented by Patel (Fig. 3.24), but without a rotating gas holder, without chambers in the digesters, but including some suggestions of Das Gupta. (All these changes were meant to reduce costs.)

It may be speculated that the main reason that government support was found [in Uttar Pradesh, Maharastra (Bombay), Saurashtra, and Gujurat] for constructing small-scale digesters, was the ever increasing use of cow dung as fuel. Until about 1930, the kitchen fuel for all but the very rich, was primarily wood. In particular from 1945 onwards, wood became increasingly unavailable; poor people who could not afford synthetic fuels, had to change to burning dried cow dung. In 1950, it was estimated that 70% of the cow dung was burnt, thus taking away the possibility of using it as fertilizer.

Within two years of the construction of the 500 plants, interest in anaerobic digestion declined. All plants that had been constructed failed in some way or other to fulfill expectations and were soon abandoned. Recently, Sathianathan (Q9) has summarized the major technical causes for this failure:

(a) In most cases a plant claimed to produce 3 m^3 of gas was constructed without reference to the needs of the family or to the availability of cow dung. In practice, almost always, gas production fell short of household needs, the gas production typically being 1.7 m^3 per day for ten months of the year, provided the digester was operated well.

(b) In estimating the gas requirements per person per day, the efficiency of burning city gas in standard burners was assumed. This has no bearing on the efficiency of the cheap tin burners used in the villages, which, in fact, use about twice as much gas. This meant that in most places, other means of heating regularly had to be used right in the middle of cooking. This irritation easily resulted in abandoning the plant altogether.

(c) The gas holder guided by a simple construction, could never be kept in a balanced position. Often, in the middle of cooking, the gas holder would tilt badly, interrupting gas supply and had to be set right before cooking could be continued. Apart from that, the pressure at which the gas was delivered to the burners was never constant.

(d) The cheap burners made from empty cigarette and shoe polish tins (as advocated by the IARI) had a very low efficiency and the flame temperature would not be higher than 200°C. Hence, cooking time was very long and some types of cooking were not possible.

Because some of the major reasons for the failure of the programme are related to the low quality or faulty designs of various appliances, after 1960 much R & D in India concentrated on these aspects. In 1959, a symposium was held in New Delhi at the World Agricultural Fair, where 13 papers were presented on cow dung gas plants (N15). Gatherings on this scale at a later date have not been reported.

3.6.4 The period 1960-1970. The developments of the last ten years of the period under review are best summarized by considering the activities of the various organizations that have been active in this field.

Khadi and Village Industries Commission (KVIC). After eight years of unsuccessful efforts to involve the authorities, J.J. Patel (referred to above) succeeded in convincing the KVIC to include anaerobic digesters in their schemes for rural development.

In 1961/62, the KVIC included in its programme, the "Gobar Gas Scheme". After some further trials, Patel's design (see Fig. 3.27) was adopted by KVIC and made available for installation at farms, giving a high incentive for doing so by providing grants and loans. In 1962/63, 315 digesters were installed; by 1970 in total, about 3000 digesters had been installed. It has been estimated that these 3000 digesters were processing about 0.02 per cent of the total cow dung production. Most of the plants were established in Gujarat.

Today (1979) about 75,000 digesters have been installed via KVIC. It seems that since the design was first introduced in 1954, nothing in the design has been changed. There have also been reports that for a considerable time, only one firm was allowed to produce and install the digesters and appliances for which purchase KVIC financial aid could be obtained. This may have restricted

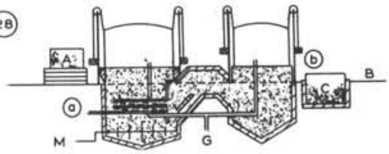


FIG. 3.28 A large-scale, two-stage digester with heating and mixing facilities designed and installed at the Gobar Gas Research Institute (Uttar Pradesh) in 1960 (N20), type "Ajitmal". The two digesters have a total capacity of 75 m^3 Inlet and outlet pipes situated at (a) and (b) are not indicated in the figure. Note the similarity to conventional sludge digesters (see Fig. 3.22). No performance data have ever been reported. It is not known how long it has been in operation.

innovation in the design, operation, and introduction of anaerobic digesters in India. It has also been claimed that the digesters installed with financial aid from KVIC, for the greater part, have been established on medium and large size farms owned by rich farmers.

Indian Agricultural Research Institute (IARI). More or less continuously, R & D related to anaerobic digestion was carried out at the IARI. In 1954, Mishra wrote a thesis on the subject, as did Prasad in 1964. After the publications on the "definitve" IARI design in 1956, minor modifications were suggested in later years (see text to Fig. 3.25). From 1960 onwards, it was in particular Idnani and Chawla who were working on the subject. At various times, attempts were made to interest farmers in installing a digester, but they were not successful (see next subsection).

Gobar Gas Research Station (Ajitmal, Uttar Pradesh). This Research Station was established in 1960 under the auspices of the Planning Research and Action Institute (PRAI) of Uttar Pradesh. Interest in anaerobic digesters developed with PRAI in 1957. Apart from being active in establishing about 100 small digesters under the scheme mentioned in the previous subsection (estimates in the literature vary from "a few" to 250), they established three large-scale digesters (20-30 m^3 gas per day) in villages near Lucknow (the gas of which was also used for running combustion engines). Because of the success of these activities, the Gobar Gas Research Station was established, of which R.B. Singh became director. The work there has mainly been concerned with large-scale digesters (an example of which is given in Fig. 3.28) and gas appliances. As far as is known, the Research Station has never been active in establishing a significant number of digesters on farms. After a publication that appeared in January 1962 (just after its inception) by the director of PRAI (N20), until now (1978) there have been no other publications dealing directly with work carried out at this Research Station. Singh has produced two books on the design and operation of anaerobic digesters covering all scales and climates, which are clearly intended for the American and European market (Q1). It is unclear whether the many drawings in these publications refer to designs that have at some time been built, or whether they have just been copied with minor variations from other publications.

Central Public Health Engineering Research Institute (CPHERI)[†] at Nagpur. This Institute started work on the subject in 1961. Its prime interest is in the digestion of night soil (N22, 36, 44), which lies somewhat outside of the scope of this review. Publications also appeared on the effect of volatile acid ammumulation (N39) and of gas recirculation in cow dung digestion (N37).

National Sugar Research Institute at Kanpur (Uttar Pradesh). Following the suggestion of a Hungarian mission (N34-35), a pilot plant was established in 1962 to study the anaerobic digestion of bagasse. It was speculated that the energy yield might be just enough to cover the heat value of burning bagasse. The advantage then, would be the fertilizer value of the spent slurry. The Hungarian experts also built a plant at the Arrey Milk Colony in Bombay, for cattle dung digestion mixed with grass. Gas production turned out to be much lower than expected and the plant was soon abandoned.

Central Fuel Research Institute at Bihar. This institute has shown an interest in continuous digestion of paddy (rice) straw. In 1964 a pilot plant was designed based on laboratory experiments (N43). The principal investigator, Goswami, later moved to the Punjab Agricultural University, where he resumed this research.

3.6.5 Evaluatory remarks. By way of general introduction, some general remarks on the problems of introducing anaerobic digesters in India have already been made in section 1.4. To this, the following points are relevant for the situation in 1970:

(a) Cooking with cattle dung fuel is extremely unpleasant (in particular in the summer) because of the smoke and the smell. Eye diseases are common where dung is used for cooking. If the dung can be processed into methane, this will affect the life of the farmer, and in particular that of his wife, considerably. Reports are given in (Q9) that support this claim. However, there are a number of other reasons why the introduction of bihugas plants in India has not been very successful.

(b) For both structural and personal reasons, the two organizations primarily responsible for the development in India: the Khadi and Village Industry Commission and the Gobar Gas Research Station in Uttar Pradesh, did not stimulate a healthy development. All in all, very little development

[†]Recently this has been renamed, "National Environmental Engineering Research Institute".

research has been carried out. As has been noted, the KVIC design has not been changed since 1954. There are various reports that other individuals who were more active in introducing new bihugas designs were constrained in their efforts by the official institutions.

(c) There has been almost no contact with other countries. The rather accidental contact with Hungary has already been referred to (sections 3.4.6 and 3.6.4). All references in the Indian literature to German experiences in this field are based on an article of Joppich, on leave in India, in Indian Farming of 1957 (N14). This is a rather awkward publication, because, amongst other things, it presents the "Kronseder"-design (no reference is made to this design in the German literature) of which it is said that "this cheap plant will be suitable for small Indian farms, as it is very simple to handle and can be constructed by village craftsmen.....". However, the picture of the "Kronseder"-design shows an electric pump for taking out digested slurry.

(d) There is rarely a direct discussion of the technical and social problems involved. An exception is (N32, 33) and also the two IARI evaluations referred to in section 6.3. From time to time, there have been general discussions in Indian news periodicals, but very little systematic effort has been made to guide the introduction and acceptance of bihugas plants.

(e) The smallest plants that are available are about 3 m^3. This is for the dung of 4-5 animals. Only two to three per cent of the farmers have so many cattle.

(f) The KVIC-design is not economically feasible. The only reason they are installed is because of the large financial support (up to 75 per cent grant and 25 per cent loan).

(g) One of the major reasons to substitute methane for burning cow dung is the fertilizer value of the dung. However, if an anaerobic digester has been installed and is working reasonably, often only the gas is used. The surplus sludge is not used on the land, because of the distance (lack of transport) and time of application (lack of storage).

3.7 Various (sub-) tropical countries

3.7.1 General. Apart from India, interest in anaerobic digestion outside Europe and the U.S.A. has been isolated and marginal before 1970. At the moment, large numbers of digesters have been installed in China, Korea and Taiwan. However, this is basically a post-1970 development. As far as there have been developments in China and Taiwan before 1970, they have hardly been documented. The same applies to the developments in Japan in the early sixties (P75).

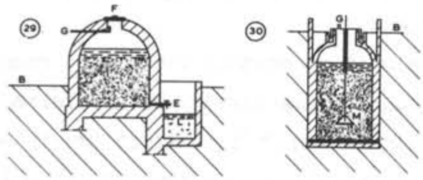


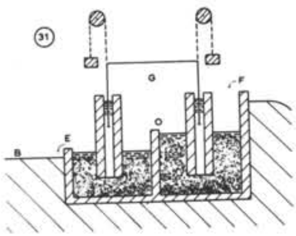
FIG. 3.29 Simple digester built of masonry and lined with plaster, suggested in a WHO-monograph (P6) for individual use in the tropics, first introduced in China. Several individual digesters might be connected to one gas holder to level out the gas availability. From the design, it would seem that unloading is rather cumbersome, unless it is assumed that the digested sludge will flow through the tap depicted at the bottom.

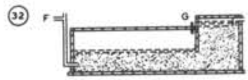
FIG. 3.30 Simple sub-soil digester which, it is said, has been in use in India. There are no feed or discharge pipes, but there is a provision for agitation of the contents (M). It is clear that unloading is particularly labour-intensive.

From the outline given in the previous sections, it is clear that the developments in the U.S.A., France, India and Germany were independent and were different in character. Developments in other European countries were induced by French or German publications. As will appear below, the marginal interests in a variety of (sub-)tropical countries were almost all brought about by a direct stimulus from either a European country, or India. This shows itself most clearly in countries belonging to the British Commonwealth. Although, as we have seen in section 3.3.5., in England itself, virtually nothing happened; the few publications that did appear triggered off all kinds of actions overseas. One of the causes for this were the articles Martin-Leake published in a number of journals that were read all over the Commonwealth (P2-5). In the French language, only one similar paper appeared (P1).

Apart from those, one might say, bilateral stimuli, there has been one international incentive: a publication of the World Health Organization of 1956 (P6). It gives a quite knowledgeable survey of the subject and presents detailed drawings of small-scale digesters and gas-holders. One of the digester designs suggested is given in Fig. 3.29. As far as can be ascertained, this publication has had no direct spin-off.

3.7.2 The Commonwealth. The publication in English agricultural journals between 1952 and 1954, and in particular the reports on the digester installed at a farm in Gloucestershire in 1954 (cf section 3.3.5) drew the attention of a number of estate owners in Kenya, South Africa and perhaps also Rhodesia.





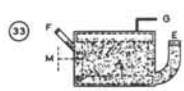


FIG. 3.31 Two-chamber cum gas holder digester, type "Transvaal", designed by Winters (P52) for warm regions. The operation is semi-continuous and presumably the major problem is the trouble caused by scum at the central overflow (O). It is not known whether this design has ever been tried out. Note the similarity to the "Bombay II" design (Fig. 3.27).

FIG. 3.32 Schematic picture of simple linear displacement reactor which has been advocated occasionally for application in warmer regions. Before 1970, the major example of this type is the design Fry used for the two digesters that were in operation at his farm in South Africa between 1957 and 1963 (Q4). The design given in the above picture contains a fixed gas holder, using the same principle of gas/liquid displacement as in the "Berlin" and "Boufarik" designs. Fry's digesters used a separate gas holder; they had heating pipes along the bottom and a complicated contraption of guiding rails to slide a "scum-drag" along the digester in order to remove the scum periodically. Apart from Fry, who had great difficulty in keeping the scum under control, no long term performance data of linear displacement reactors have been reported.

FIG. 3.33 Digester used by Boshoff (P31) for continuous digestion of fibrous materials, type "Makerere". The agitator is an open structure (as distinct from the rotating perforated drum used in the "Illinois" design - see Fig. 3.21). Boshoff found a significant increase if the contents are agitated. Comparing this with the text to Fig. 3.23, it may be speculated that, if agitation is considered, it should be such that it whirls up the sludge lying on the bottom of the digester and/or breaks up the scum layer. The "Makerere"-design seems to fulfill this criterium quite well.

(The existence of an anaerobic digester on a farm near Salisbury has been reported in 1961 (P7), but no further details are known.)

In *Kenya*, T. H. Hutchinson started digesting pig manure in 1954. In 1955, he built a digester which is alleged to have produced about 12 m^3 of gas a day, which was used as a domestic energy source. However, his main interest was in up-grading the manure of his coffee estate. Hutchinson claimed in 1962 that he had obtained a steady increase in coffee yields (P37). His optimistic views were later disputed in a publication of the Coffee Research Station in Ruiru (P38), in which it was stated that Hutchinson's soil was in a good state of fertility, but that the quality of the leaves and cherries of the plants were not as good as they might have been if synthetic fertilizers of a balanced composition had been used. Since 1957, Hutchinson started marketing four types of "digester kits". It is not known how many of these have been sold.

In *South Africa*, at least three farmers engaged in anaerobic digestion as a result of the British publications: Rowan, Winters and Fry. It seems that they did not have any contact with each other, although they all started their activities around 1955. Rowan's digester (basically an "Algeria"-type) gave rise to many enquiries when referred to in publications in the South African journal Veldtrust (P41), but apparently nobody followed his initiative. Winters designed two or three digesters, the most original of the designs being represented in Fig. 3.31. For some reason, his activities generated most interest in *Australia* and *New Zealand*, where articles on his work (which also summarized the English and German literature on the subject), stimulated hundreds of letters to the editors of "Power Farming and Better Farming Digest" seeking further information. However, as far as is known, no digesters were ever actually build in New Zealand. (This was in accordance with the opinion of the editors of the journal just mentioned: "it is very doubtful as to whether the production of methane gas in Australia and New Zealand is a practical proposition".)

In recent popular publications on anaerobic digestion, the name of Fry is often mentioned, and he is referred to as "one of the leading exponents of the art of running digesters in practical situations". This is because of two publications of his (Q3,4) that have been sold in large numbers. After some preliminary work, he installed two full-scale displacement digesters (cf. Fig. 3.32) on his 1000 hog farm in 1957. These digesters were in operation for six years and eventually gave a gas production of 230 m^3 per day. Fry's digesters did not give him an economic benefit. However, he was the first (and up till recently the only one) who experimented with a large-scale linear displacement digester, although most of the time he was not operating - but developing the digester. Insufficient details are available on the final design and its performance to judge its feasibility. On the basis of the pictures and text in (Q4), it would, however, seem that the design has become very complicated as a result of trying to overcome all practical problems in operation.

After the 1957-58 publications, there are no further reports in the South African literature, indicating that the initiatives of Rowan, Winters and Fry apparently were not taken over by others. In 1966, a publication appeared drawing attention to the potentialities of anaerobic digestion for warm areas. A photograph and further details are given of an oil-drum-digester in operation at the Glen College of Agriculture (P44). However, this did not stimulate further interest.

In *Uganda*, Boshoff carried out a research project on the potentials of using vegetative wastes (such as sweet potato tops and plantain peelings) to produce methane via anaerobic digestion (P31-33). This project was financed by the (British) Tropical Products Institute. The pilot-plant digester that was used, is depicted in Fig. 3.33. Some of his results are referred to in the next chapter (see in particular Fig. 4.1).

3.7.3 Francophone countries. In the French and Belgian literature, there have been occasional references to the potentials of small-scale anaerobic digestion in the tropics. Because of the higher ambient temperature, heating would be unnecessary (it was argued) and this took away the major economic constraint. In a 1947 publication (P1), reference is made to digesters in Madagascar that were working satisfactorily. One may speculate that there must have been more attempts in French-speaking tropical countries to take advantage of anaerobic digestion, but no reference to this have been found in the literature.

3.7.4 Latin America. In Germany, some laboratory research was carried out on the digestibility of tropical products such as sisal waste, grapes and coffee husks (G34, 51). It was said that "Coffee husk has been found to be a rich source of methane, and there are several plants operating in Central and South America on this material, and on some other local vegetable wastes". However, no further information on this could be found, with the exception of a publication of a coffee research institute in *Columbia* (P11), which in fact reports problems in digesting coffee husks due to souring.

3.7.5 Middle East. Interest was shown in the digestion of manure in *Israel* (P21,22) and in 1958, an experimental digester ("Algeria"-type) was constructed at the Agricultural Research Station in Beth-Dagon. Methane fermentation was proceeding satisfactorily, but the work was not continued because investment and operation costs were considered too high.

In *Egypt*, the Department of Agriculture initiated a research project on anaerobic digestion in 1966 to see whether this offered the possibility of making some use of crop residues (cotton, maize, rice). Some results of this

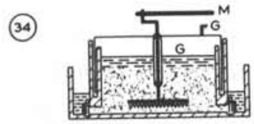


FIG. 3.34 Batch digester, type "Fuyang", of which it is said that 48,000 were in operation in China (Northern Anhwei province) in 1959 (P61). The digesters are built using bricks (size 3-13 m^3) and loaded with farm yard manure and vegetative waste as available. The hand-stirrer is used to release the gas bubbles from the sludge. Further details are unknown. Judging from the design, which is reproduced as given in (P61), there may well have been problems in operating it.

project are discussed in the next chapter (see in particular Fig. 4.4).

3.7.6 South-East Asia. Very little has been published on the developments in South-East Asia. There is a 1959 publication from *China* (P61) referring to 48,000 digesters in operation in the county of Fuyang alone. The digester design used is reproduced in Fig. 3.34. The reliability of this publication as well as the extent to which developments took place in China before 1970 is difficult to judge.

From about 1960 onwards, anaerobic digestion has been applied on hog farms in *Taiwan*. No detailed information is available, but it may be assumed that this development is basically concerned with medium-scale anaerobic digestion (P65).

There is a 1964 publication from *Thailand* in which the Indian IARI-design (Fig. 3.25) is advocated. Very few digesters had been installed in Thailand before 1970.

In *Korea*, the government launched a program in 1969 to install large numbers of 6 m^3 "Household" digesters. These are made from concrete, below ground level, no heating, and with a gas holder as cover. Their actual operation is about eight months a year. The evaluation of this programme falls outside the time limits of this review.

Work in *The Philippines* started soon after an official mission of the Philippine Coconut Administration returned from Europe in 1965 with enthusiastic reports of bihugas developments in Germany.

4. GAS YIELDS OF AGRICULTURAL WASTES

4.1 Specific gas production

4.2.1 General outline. In publications drawing attention to the advantages of biogas production, figures are usually quoted to indicate how much gas can be obtained from a certain amount of organic waste. The practical relevance of such promotion data is often quite insignificant. For example, if the theoretical gas yield (i.e. assuming that all carbon is converted to methane) for sawdust is quoted to be 1.9 m^3 gas per kg dry sawdust (Q21) then this is misleading, even if it is added that in practice, one usually will not reach theoretical yields; because in fact, under the very best circumstances, gas yields can be obtained of only 0.01-0.1 m^3/kg (M29). Of course, the discrepancy is not so extreme for many other wastes, but it will be clear that great care should be taken in accepting such theoretical data on face value as a basis for evaluating the feasibility of small-scale digesters (or for that matter, large-scale digesters as well).

In a way, it makes no sense to speak about the specific gas production, α, of various materials, because the α observed in a particular case is dependent on so many parameters. However, before embarking upon a more detailed discussion of the data for α given in Tables 4.1-4.5, a bold generalization seems to be in place. This generalization consists of three parts:

(a) Theoretical specific gas yields for natural organic materials come in the range of 0.7-3.2 m^3/kg. These values are never reached in practice.

(b) No matter what feed is used, specific gas yields in the range of 0.1-0.3 m^3/kg are obtained in reasonable times (see on what is reasonable, section 4.2) at 30°C provided the digester is operated properly. Whether one will be nearer to 0.1 or to 0.3 m^3/kg depends more on the design and the operation of the digester than on the particular feed.

(c) If the digester is not operated properly, any gas production is a matter of pure luck.

4.1.2 Reliability of data for α. The most extensive study on the specific gas production of various materials was carried out by Reinhold and Noack (see text to Fig. 4.2). They emphasized that their results can only be generalized "cum grano salis", and that it is impossible to give a precise measure of the error and the reliability of the data. Data reported on the basis of less detailed studies should be evaluated in this light. The data collected in Tables 4.1-4.5 indicate that most natural organic materials can be digested. The major factors influencing the reliability and significance of the data reported can be summarized as follows:

(a) The total specific gas production, α (m^3/kg), is related to the suspended solids reduction, β (per cent weight reduction). In the tables, most data are for α, but there are also studies in which only (or also) β is measured. Ideally, mass balances for carbon and nitrogen should be obtained when carrying out digester experiments. Only in that way can one be sure that the data obtained are true for the particular experiment that was carried out. Attempts to establish such balances are extremely rare (G15,49).

(b) The specific gas production is defined as m^3 total gas (per kg of dry material). To know the (calorific) value of the gas produced, one needs to know the methane content. It would be better to compare the specific methane production (instead of the specific gas production), because large amounts of carbon dioxide produced may find their way as carbonates in the liquid or solid residue phase, in particular in (semi-) continuous operation. Usually, the methane content also varies in time, in particular in batch experiments. However, given the way most experiments have been carried out, total gas production is a more reliable figure than methane production.

(c) The specific gas production is defined per kg of dry material. Methods to determine the moisture content of samples are often not very reliable. However, a small percentage of water in the dry material does not upset the accuracy of the data for α very much. More important is the distinction between dry organic material and dry material (total). Data quoted in the tables are meant to be for dry material (total), but often the original sources are ambiguous in this respect. Again, it would be better if the organic dry matter is always determined, and the gas production based on this.

(d) The gas production is, of course, a function of time. Although in the tables, some data are given for α in semi-continuous experiments, in general, the implicit or explicit intention of the data of α quoted in the literature, is that it is the maximum gas yield, which is obtained in a batch experiment. There are two aspects to this. First, the times involved to reach the maximum gas production are often extremely long, therefore the practical relevance of these data is low. That is to say, to take an extreme example, it is of little practical interest to know the amount of gas than can be obtained from straw in 600 days. Secondly, because the time to reach "equilibrium" was so large in many studies, a rather arbitrary time was taken for which the gas production is reported. For this reason, in general, the data for α given in the tables cannot be compared very well. It can further be seen from Tables 4.1-4.5 that it is very common to report values of α without indicating the time over which the gas was collected. The function $\alpha(t)$ is further discussed in section 4.2.

(e) The specific gas production is, in general, a function of the temperature. However, often the temperature at which the data for α are obtained is not quoted in the literature. The function $\alpha(T)$ is further discussed in section 4.3.

(f) The specific gas production is a function of a large number of other parameters, some of which are discussed in sections 4.4-4.6. The most probable causes for relatively low data for α appearing in the tables are: overproduction of volatile fatty acids, which inhibits gas production, either directly or via the pH; low nitrogen content of some feeds; and difficult hydrolysis of cellulosic materials.

(g) Often an inoculum is used to start digestion, often in large quantities of the organic material present (10-25%). Unless careful comparisons are made with digesters containing only the inoculum, reported data for gas production may well be too high.

4.1.3 Elucidation of the tables. In Table 4.1, reported data are given for dung and manure from the most common farm animals. Although it has been stated in the literature that the ease of digestion increases from cow to swine to horse, it seems that on the basis of the data collected, at least for the maximum specific gas production, this conclusion is premature. Not enough data are available to draw any conclusions concerning the influence of the type of animal or the geographical region. A priori, it should be expected that cow (and sheep) dung contains less digestable materials because they are ruminants. In interpreting the data, it should also be realized that the composition of dung may be very different, depending on the age and race of the animals, the type of food they get, how they are kept, etcetera. As far as the influence of the straw in the manure is concerned, it may be expected that the form of the straw is more important than the particular type of straw (cf. section 4.4).

Data are available on wastes of all major cereal crops with the exception of millet (Table 4.2). There is no reason to expect that millet wastes would digest very differently. In comparing the different crops, it is of importance to note that maize and rice are quite different from the rest. In particular, rice husks and maize cobs are very different from the other sheaths. It is difficult to assess as to whether the low value of α for rice husks is

TABLE 4.1 Selected data on the specific gas production, α, of animal excreta and manure (dung + straw). Under "remarks", t gives time in days (residence time or duration in batch experiment). T is temperature in °C. If the temperature is not given, it may be assumed that in laboratory experiments (indicated by L) the temperature has been 30°C, and for digesters in practice (P) it has been ambient temperature. Only in a few cases is the solid concentration known, C(% weight). In almost all cases the methane content of the gas can be assumed to be between 55 and 65%. η is the loading (kg dry solids/m³ reactor volume) in semi-continuous experiments. Cf also text to table 2.1.

feed, country	α(m³/kg)	remarks	references
(a) cow dung			
Germany	0.23	L, T = 30, 75-80% CH_4, no difference between seasons	G42
USSR	0.31	L, 60% CH_4	M27
India	0.3	L, data quoted, experiments not described	N14,27
India	0.1 -0.3	P, range for summer and winter ambient temperature	N13,48
India	0.23-0.50	P, as quoted by Loehr and Agnew (1963), in (Q17)	
(b) cow manure			
Germany	0.23-0.27	L and P	M4
France	0.20-0.33	P, C = 15-25	F9,12,15,32,34
USSR	0.18-0.23	t = 30, T =32	M21,27
USA	0.16-0.19	L, t = 100, T = 25-30	L7
Israel	0.09(?)	L, t = 60	P22
(c) swine dung			
Germany	0.26-0.39	L, T = 30, winter, summer feed resp., 80% CH_4	G33
(d) swine manure			
Germany	0.5 -1	source of data unclear	G33
USSR	0.2		M27
Taiwan	0.24	t = 60	P65

TABLE 4.1 (cont'd) Specific gas production of dung and manure

feed, country	$\alpha(m^3/kg)$	remarks	reference
(e) horse dung			
Germany	0.38	L, no difference between summer and winter feed, 80% CH_4	G42
(f) horse manure			
Germany	0.25-0.38	P, T = 30	A7, G18,33
USSR	0.18		M21
(g) sheep manure			
Germany	0.37-0.61	source of data unclear	G33
USA	0.12-0.32	t = 20, T = 35, C = 5	L12

TABLE 4.2. Data on the specific gas production, α, for cereal crop wastes. All data are for batch laboratory experiments, unless otherwise indicated. See further text to table 4.1.

feed	$\alpha (m^3/kg)$	% CH_4	t(days)	remarks	reference
(a) straw or stalks					
wheat	0.1 -0.2	55	20-180	presumably inappropriate inoculation	E5
	0.15-0.25	50-55	20-30	semi-continuous, 5 m^3 reactor	L7
	0.32-0.35	60	60	see also Fig. 4.5	F20, G33, 36, L7,9
barley	0.11-0.15	53	180	cf low values for wheat	E5
	0.33-0.37	60-70	120		F20, G33
rye	0.27-0.32	64	30-100	for France, Germany, and USSR	F20, G33, M21
oats	0.37	70	70		E5, F20, G33
sorghum	0.33	60	70		F20
rice	0.16	52	180	probably too low	E5
	0.27-0.34	80	85		G33, N44
maize (corn)	0.20-0.42	55	30-60	α up to 0.52 for flour (L9) or 0.58 for t = 600 (L7)	F20, M27
	0.13-0.20	55	16-60	semi-continuous, 5 m^3reactor	L7
(b) seed sheaths					
wheat chaff	0.34	73		see Fig. 4.2	G33
barley chaff	0.37	76		see Fig. 4.2	G33
rye chaff	0.37	73		see Fig. 4.2	G33
oats chaff	0.33	70		see Fig. 4.2	G33
rice husks	0.05	62	32		L7
maize cobs	0.23-0.42	60	60	USSR and USA respectively	L7, M27

significant. (As rice husks have many more valuable potential applications than anaerobic digestion, this is, in practice, not very important.) In traditional agriculture, straw has always been used as a source of compost for the soil. Rice straw (much more so than the other straws) contains a large amount of nitrogen, phosphorus and potassium, which should therefore preferably be returned to the field. It follows therefore, that in general, any use of such "wastes" as an input for a methane digester can only be an alternative way of composting.

In Table 4.3, the data for fibre crop wastes and related types of stalks, straw, and twigs are presented. Of course, many of these materials have important applications. They are not, strictly speaking, "wastes" (although some more so than others). For example, bagasse is usually the main source of energy in sugar production. Whether the alternative route to energy via digestion is perhaps to be preferred is a difficult question. The high value for cotton fibre is almost certainly significant because of its very high cellulose content. Similarly, the low values for cattails and reeds are probably significant, because of their low cellulose content and the problematic hydrolysis (see on this section 4.4).

Available data on leaves, grasses, and whole plants are given in Table 4.4. In general, green plant parts seem to digest well (see on the kinetics, also next section). Because chestnut leaves did not digest, whereas other leaves did, it has been speculated that this is due to the presence of tannic acids, which are assumed to inhibit digestion (A7). Most of the data for leaves and grasses were collected because of their presence (in small quantities) in the soil and in manure; and in most applications they will be part of a mixture that is digested. More recently, a number of grasses have also been considered as energy crops (D8, 10).

Finally, in Table 4.5, data are collected for forestry wastes, peat and soft coal, and three miscellaneous husks. (Perhaps the latter may as well be compared with the materials in Table 4.3.) The digestibility of peat is a matter of dispute. Certainly the gas production is low due to the very low cellulose content. The low values for a number of forestry wastes are probably related to the inaccessibility of digestable materials (cf section 4.4 on form of material) and absence of nutrients, or presence of inhibitors. That is to say, in the case of forestry wastes, it is certainly more difficult to get the conditions right than in the case of, say straw, but presumably, in theory, similar gas yields can be obtained. Because forestry wastes usually have a lower water content than other organic wastes, other routes to energy may be more attractive, unless great value is placed on producing compost from these wastes.

TABLE 4.3 Data on the specific gas production, α, of fibre crop wastes and various stalks and straw-types. All data are for batch laboratory experiments. See further text to tables 2.1 and 4.1.

substrate	$\alpha (m^3/kg)$	β(%)	t(days)	% CH_4	remarks	reference
banana skins	0.36-0.41				α = 0.04 in (D1)	L7, G33
banana stems	0.38	43	62	62	α = 0.54 in (G33)	L7
cotton stalks	0.33					F20
cotton fibre	0.6		100	60	T = 35°C	F20
flax straw	0.30-0.36	30 (?)	30-60	58	t = 20 for T = 52 (L8)	F20, L7, 8, M27
freshly harvested flax	0.23		100	72		L7
flax shives	0.24		62	58		L7
bagasse	0.33	50		62		L7, P65
rapeseed straw	0.34					G33
soybean vines		47	50		β = 39 at t = 15	L7
sunflower stalks	0.30	61	60		β = 29 at t = 15	L7
vineyard stalks	0.26		120	60		F20
fruit tree twigs	0.37					M71
cat tails	0.13	13	62	61		L7
reed	0.15-0.19				α = 0.28 in (G33)	G34

TABLE 4.4 Data on the specific gas production, α, of leaves, grasses, and whole plants. All data are for batch laboratory experiments. In most cases the temperature can be assumed to be about 30°C. Other related materials that have been quoted as digesting well include plantain peels, papyrus, paspalum (all P33), and vine prunings (F29). See also text to tables 2.1 and 4.1.

substrate	$\alpha(m^3/kg)$	β(%)	t(days)	% CH_4	remarks	reference
(a) leaves						
sugar beet	0.43		14	84		G33
potato plant	0.26-0.53			60-75	α = 0.26 (M27)	A7, G4,33
maize	0.48			83		G33
peanut plant	0.3		170	60		F20
tree leaves	0.15-0.22			59		M27
bracken leaves	0.11		180			E5
various	0.29		62	59		L7
(b) grasses						
lawn mowings	0.22		180			E5
various (Northern Europe)	0.3 -0.5		30	70-80		M27
alfalfa	0.33-0.63	45	62	57	details behind α = 0.63 unclear(M71)	E2, L7
elephant grass	0.38-0.57				T = 32; α = 0.25-0.44 at T = 22	P31
(c) whole plants						
clover	0.25-0.41		120-30	65-78	F20 and G33 respectively	F20, G33
pithy weeds	0.02	15	62			L7
non-pithy weeds	0.12	15	62		α = 0.62 (?) in (M71)	L7
heather	0.43			76		G33
algae	0.6		20		T = 43	D22
mushrooms	0.12-0.32					M71

TABLE 4.5 Specific gas production, α, of various organic materials. See parallel text to tables 2.1 and 4.1.

substrate	α(m^3/kg)	β(%)	t(days)	% CH_4	remarks	reference
(a) dead materials						
peat	0.015					G33
soft coal	0.11		131	79	T = 22-28	L7
(b) forestry						
fir tree needles	0.31			70		M27
pine tree needles	0.04		63	69	α = 0.11 if alkali treated	L7
spruce sawdust	0.02-0.13		30		cf Fig. 4.14; α = 0 in (F20)	G33, M30
aspen sawdust	0.01-0.05		30		cf Fig. 4.14	M30
wood wool	0.27	30-34	62	54		L7
sweet wood	0.07					P15
wood flour		20	76			L7
(c) miscellaneous						
coffee shells	0.31		21		T = 35	G51
peanut shells	0.10	12	62	60	T = 22-28	L7
pea pods	0.10	12		60		G33

4.2 The kinetics of gas production

4.2.1 Simple model to represent the data. Data for gas production during anaerobic digestion are usually plotted in one of the following ways:

(a) specific gas production, $\alpha (m^3 kg^{-1})$, versus time, t (cumulative);

(b) gas production, $\emptyset$ (m^3), versus time, t (cumulative);

(c) gas production rate, $d\emptyset/dt$ $(m^3 d^{-1})$, versus time;

(d) specific gas production rate, $d\alpha/dt$ $(m^3 kg^{-1} d^{-1})$, versus time.

In the literature here reviewed, graphical representations are usually of the form (a) or (b). Because the rate of evolution of gas over the fermentation period is not constant, but is initially high and then decreases steadily to reach a level which can hardly be measured, the curves obtained when plotting any of the above pairs of parameters do not have a simple form. The possibility of postulating simple models for the kinetics - for example, the Monod model - is well-known from microbiology, but in the literature here reviewed, attempts to plot the data in such a way that a straight line might be observed have not been made.

The following model is here introduced solely to present the data in a simple way. To this end, we assume that at any particular time, the specific rate of gas production is a linear function of the concentration of organic matter still to be decomposed. We may then write:

$$d\alpha/dt = k\ (\alpha_{max} - \alpha) \qquad [1]$$

with α the cumulative specific gas production at time t, α_{max}, the maximum specific gas production ($t = \infty$), and k a reaction velocity constant.

We define the relative specific gas production, ω, as follows:

$$\omega \equiv \alpha/\alpha_{max} \qquad [2]$$

The range of ω is from 0 to 1, or, alternatively, from 0 to 100%. Eq. [1] can then be rewritten as:

$$d\omega/dt = k\ (1-\omega) \qquad [3]$$

and integration yields:

$$\ln(1-\omega) = -\ kt \qquad [4]$$

If this model applies, then (ω, t) plotted, using appropriate scales, should yield a straight line. This has been done in Figs. 4.1-4.5. Although various types of deviations of the straight line occur, the number of cases in which over the whole interval, quite accurate straight lines are observed, is considerable. It is therefore concluded that the model suits the purpose of providing a simple empirical law-like description of the phenomena.

In the literature under review, the fact that this way of plotting the data has never been considered, may be interpreted as an indication of the lack of

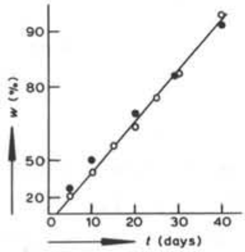


FIG. 4.1 Specific gas production of elephant grass, measured by Boshoff (1967, P33). The experiments were carried out with about 8 g grass in 300 ml digester flasks, using residues from a previous digestion as a starter. The open circles are for digestion at 22°C; there is no significant difference with digestion at 32°C (closed circles). See on experimental details also (P31).

scientific competence in all this work. Boshoff (P33) is the only one who applied this model (being aware of literature on sewage sludge digestion using this approach), but he curve-fits the data directly on

$$\alpha = \alpha_{max}\ \{1-\exp(-kt)\} \qquad [5]$$

The data on the digestion of elephant grass he gives as support for this model, are plotted in the way proposed above in Fig. 4.1. As can be seen, the agreement with a straight line through the origin is quite good. The advantage of curve-fitting the data (α,t) on eq. [5] is that one does not need α_{max} (which is presupposed in w). The disadvantage is that one obtains other data, viz. (α_{max}, k), but no suitable visual representation.

4.2.2 Some experimental data. The most comprehensive studies on the kinetics of gas production of various agricultural wastes, have been carried out by Reinhold and Noack (Fig. 4.2), and Nelson and collaborators (Fig. 4.5). The results of the latter will be discussed in the next section on the effect of the temperature. The experimental results of Reinhold and Noack are presented in six groups: straw (I), straw chopped to different sizes (II, the effect of the form of the material is discussed in section 4.4), animal excreta (III,IV), miscellaneous plant materials (V), and chaff (VI). As can be seen, in many cases, the model is confirmed well; in other cases there are various types of deviations. One has to be careful with giving specific explanations for such deviations. There are numerous possibilities for a particular set of data to be less reliable. It may just be that which causes the deviations. On the basis of the latter assumption, one may speculate that the data for excreta of animals on winter feed are more "ideal" than for animals on summer feed, because the substrate is more homogeneous. Similarly, straw carefully chopped up in one particular size will yield more systematic results than "random" straw.

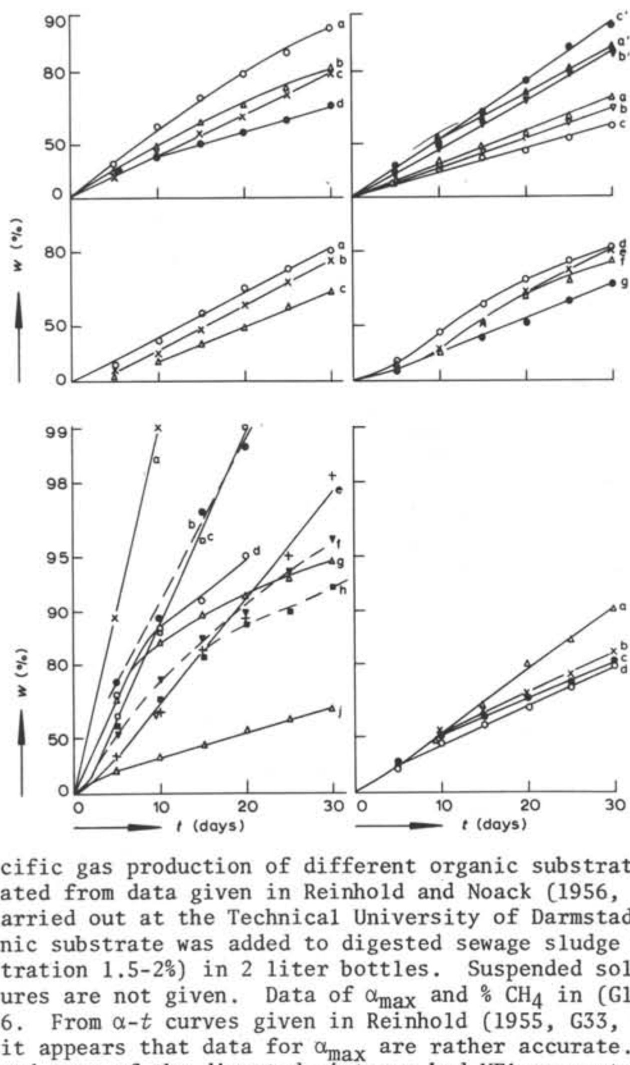


FIG. 4.2 Specific gas production of different organic substrates at 30°C. Curves calculated from data given in Reinhold and Noack (1956, G42), based on experiments carried out at the Technical University of Darmstadt during 1952-54. The organic substrate was added to digested sewage sludge water (suspended solids concentration 1.5-2%) in 2 liter bottles. Suspended solids concentrations of mixtures are not given. Data of α_{max} and % CH_4 in (G16, 31) - see Tables 4.1-4.6. From α-t curves given in Reinhold (1955, G33, partly also in G42 and G63) it appears that data for α_{max} are rather accurate. However, both the inoculum and most of the digested mixtures had VFA-concentrations of 500-3000 mg/dm^3 (G42). For manure, straw, and chaff, observations were also made of colour, odour, sediment, and scum layer thickness at the end of digestion.

I (top left), straw, (a) oats, (b) wheat as well as barley, (c) rye, (d) rape-seed;

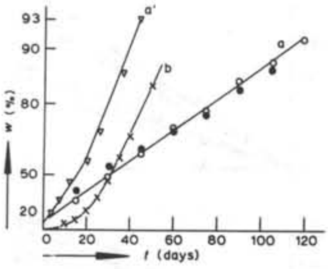
II (top right), straw, (a) rice, 3 cm, (a') 0-2 mm, (b) rye, 3 cm, (b') 0.2-0.5 mm, (c) wheat, 3 cm, (c') 0-2 mm;

III (centre left), animal excreta (winter feed), (a) horse, (b) swine, (c) cattle;

IV (centre right), animal excreta (summer feed), (d) horse, (e) swine, (f) cattle, (g) cattle manure (excreta + straw);

V (bottom left), various vegetable materials, (a) sugar beet leaves, (b) clover, (c) grass, (d) mangold leaves, (e) heather, (f) maize leaves, (g) potato leaves, (h) plant seeds (mixture, at 37°C), (j) reed;

VI (bottom right), (a) oats, (b) barley, (c) wheat, (d) rye.



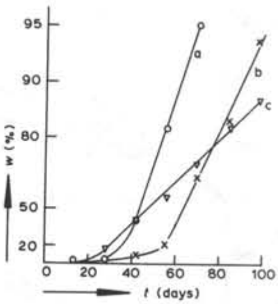


FIG. 4.3 Specific gas production of (a), (a') manure and (b) cotton fibre. Calculated from α-t curves measured by Ducellier and Isman (F20). Curve (a') is for 40 m^3 manure (including 60-80% water). Curve (a) is also for a large unspecified quantity of manure; other data not given. Presumably (a') has been obtained at a higher temperature than (a). Curve (b) is for 20 g of cotton fibre, digested at 35°C.

FIG. 4.4 Specific gas production at 30°C of (a) rice straw, (b) cotton stalks, and (c) a mixture of rice straw, cotton stalks, maize stalks, and dung, measured by Rizk et al (1968, P25). In the case of (a) and (b), 5-10 g was digested in a 250 ml flask using dung as a starter; (c) is for 156 g of the mixture in a 5 l flask.

Because so many variables affect the gas production, comparison of the slopes for different materials (a measure for the ease of digestion), is dangerous, particularly if the data stem from different sources. Analyzing only the data of Reinhold and Noack, it seems reasonable to conclude that all materials depicted in subfigure V except reed (that is: all green plant parts) digest much more quickly than straw, chaff, and animal excreta. The differences between the latter three are not significant. (On the other hand, they do not falsify the general opinion that straw, particularly if chopped, digests better than excreta.)

The data presented in Fig. 4.2 are for small-scale laboratory experiments. The data for manure in Fig. 4.3 illustrate, first, that straight lines may also be observed for large-scale installations, and second, that there can be large differences in the rate of digestion for the same material [as curves (a) and (a') are both for manure].

Often an adaptation period is observed before digestion starts properly and the model is observed. An extreme example of this is given in Fig. 4.4, where the adaptation time is as high as 50 days for cotton stalks [although a starter (inoculum) had been added]. Note that by plotting the data as advocated here, the adaptation time is easily recognized and quantified. Perhaps it should be stressed once more that, given the reliability and reproducibility of the experimental technique together with the number of systematic studies presently available, extreme care should be taken in not reading too much into the data. For example, the reaction velocity constant for cotton fibre in Fig. 4.3 and for cotton stalks in Fig. 4.4 is exactly the same. There is, however, very little ground for any other explanation than pure chance.

4.3 The effect of temperature

The interest in the effect of temperature on the maximum specific gas production and the gas production rate, falls roughly into three areas: absolute temperature, temperature fluctuations, brief exposure to high temperatures.

4.3.1 Absolute temperature. It has often been suggested, both in the past and recently, that because microbes can in general adjust themselves to new environments by selection, it should be possible to "breed" microbes that work well at any chosen temperature (in particular lower temperatures would be advantageous, because no heating is necessary to achieve maximum gas production). There is no reason to expect very much of this. First, in anaerobic digestion, many different microbes have to live together, hence it is doubtful that they can all be optimally adjusted to the same temperature. Second, although not much is known of the precise mechanism of hydrolysis of complex substrates, it may be expected that the rate of hydrolysis will always increase with increasing temperature. Third, anaerobic digestion has occurred naturally for millennia, usually at low temperatures. Hence, one would expect that whatever microbes can exist that grow fast at temperatures in the range 5-25°C would by now be present in nature.

Roughly speaking, only three temperatures (ranges) are considered for anaerobic digestion: (i) ambient temperature, (ii) 30-35°C (mesophilic digestion), (iii) 50-55°C (thermophilic digestion). The first possibility derives from practical considerations. The other two are the available optimal temperatures according to the theory of microbiology. For the systems under review here, it is however unclear whether the gas production rate just increases with absolute temperature or whether there are really optimal regions.

The difference between mesophilic and thermophilic digestion is illustrated in Fig. 4.5 for a number of cellulosic materials. The maximum specific gas production is not significantly dependent on the temperature. It can be seen that on the whole, the dependence of the reaction velocity constant on the temperature, is similar for most materials. Data for manure digested in the mesophilic and thermophilic range are given in Fig. 4.6. Because the maximum gas production rate was difficult to estimate, the actually observed gas production rate is plotted. An advantage of plotting the data this way is that

TABLE 4.6 Selected data on the temperature dependence of the total specific gas production (m^3/kg). The absolute values of the data cannot be compared, because (i) gas production, in some cases, is only given for total weight of feed, whereas the solids concentration is not known, (ii) the time over which the gas production is added varies and equilibrium has not been reached in all circumstances; t gives time in days.

temperature (°C)	cow dung (N6) t = 15	manure (M71)	maize stalks (L7) t = 50	rice straw (E5) t = 180
10		0.45		
15		0.53		
20		0.61	0.36	0.024
25		0.71	0.46	0.09
30	0.0	0.76	0.48	0.19
35				0.20
40	0.046			0.11
45				0.022
50	0.062		0.49	
55	0.055			

the choice of the optimal residence time is easier to visualize.

The number of studies on the influence of the absolute temperature is very limited. Apart from the data presented in Figs. 4.5 and 4.6, not more than four other publications are available. They are summarized in Table 4.6. These data are given for reasons of completeness only; in all cases, there are good reasons to doubt their reliability.

Although we have seen in the previous chapter that the largest number of publications on anaerobic digestion of agricultural waste stems from France and Germany, there have been no significant contributions concerning the temperature effect from this side. In the German literature, reference is always made to the data of Fair and Moore obtained for sewage sludge (B7). Some of their data are given in Fig. 4.7. Given the composition and constituency of sewage sludge, the relevance of these data for agricultural waste substrates is doubtful. In the French literature, often tables are given for the gas production per day as a function of the temperature. They suggest that the gas production is doubled every five degrees from 10 to 35°C (F32,33, H3). However, these data refer to different digestion times, and experimental details as to how they have been obtained are not given.

4.3.2 Temperature fluctuations. It is generally assumed in the literature on anaerobic digestion that the microbes are very sensitive to small fluctuations in temperature. Although there seems to be some theoretical support for

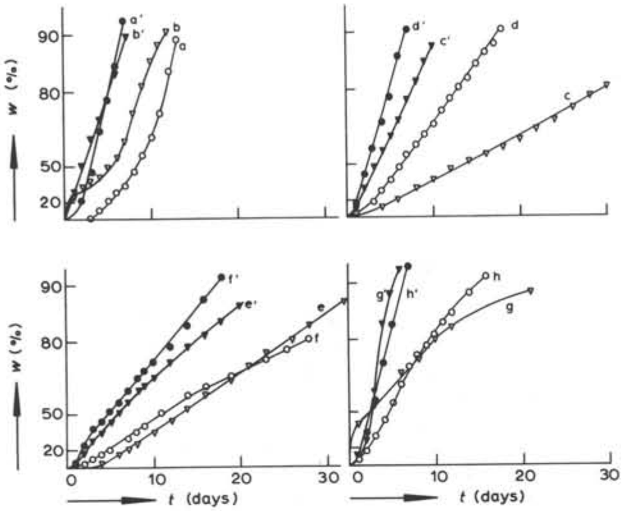
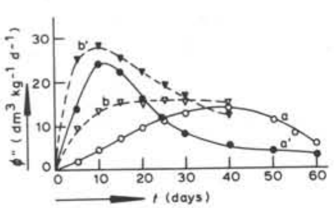


FIG. 4.5 Specific gas production of various cellulose-type materials as a function of temperature, chemical composition, and size of particles (Nelson, Straka, and Levine, 1939, L9). These experiments were carried out in 1-5 liter flasks at the Industrial Farm Products Research Division of the U.S. Department of Agriculture. (a)-(h), 28-30°C; (a')-(h'), 50-55°C. (a) filter paper, (b) "cook liquor" (the liquid residue left after digesting maize stalks with alkali for the purpose of manufacturing wallboard), (c) chopped maize stalks, (d) maize stalk flour, (e) chopped wheat straw, (f) ground wheat straw, (g) artichoke top flour, (h) seed flax straw. For (c), (c'), (e), (e'), (f), and (h) estimates had to be made of α_{max}, as digestion was not complete when the experiment was finished. For maize stalks (chopped and flour) the decomposition of cellulose, pentosans, and lignin was also followed separately (L8).



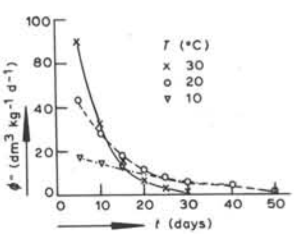


FIG. 4.6 The influence of temperature on the gas production rate of manure: (a), (b) at 30°C; (a'), (b') at 50-53°C; (a) and (a') as measured by Ananiashivili (1957, M22); (b) and (b') by Klawenek and Pentkowski (1962, M64) for 1000 kg manure. The difference is probably due to the difference in suspended solids concentration, being 20% in the first case, and 8% in the second.

FIG. 4.7 The influence of temperature on the gas production of sewage sludge between 10 and 30°C, as measured by Fair and Moore who carried out numerous studies concerning the temperature dependence of sewage sludge digestion (B7). Large differences are possible between different types of sludge. With varying success they could apply the Arrhenius equation for the temperature dependence. Systematic measurements on the gas production rate of manure as a function of temperature below 30°C are not available.

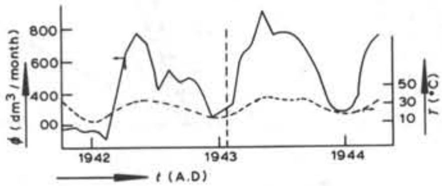


FIG. 4.8 Effect of daily temperature on the gas production of a 1 m^3 cow dung digester, operated at ambient temperature at the Indian Agricultural Research Institute from October 1941 to May 1944 (Desai and Biswas, 1945, N2). The data plotted are averages over one month. The effect of summer and winter is apparent. Until January 1943, more dung was added than digested, sludge being taken out. From then on, the digester operated semi-continuously, processing 150 kg cow dung per month (the output of about one cow). The specific gas production is rather low, because the primary research interest was in the fertilizer value of the digested material. (No significant difference was found between farmyard manure prepared in different ways, by anaerobic fermentation or otherwise.)

this, no systematic studies on this aspect have been reported. (In digestion experiments with various soluble organic pure substances carried out at this laboratory, occasional temperature drops in an otherwise constant-temperature-room did not have a noticeable effect).

The effect of temperature fluctuations is of prime interest if digestion is considered at ambient temperatures. In this case, one has to distinguish between short-term fluctuations (basically the day/night cycle and rapid changes due, for example, to oncoming storms) and long-term fluctuations over the seasons. The effect of the latter is illustrated in Fig. 4.8. One may conclude that on average, there is a good correlation: a higher ambient temperature in the range 10-40°C yields a higher gas production. No other systematic correlations of ambient temperature and gas production have been reported.

4.3.3 Brief exposure to high temperatures. This aspect is of importance in connection with the alternatives available for heating the digester contents. If hot water or water vapour is injected into the reactor for a brief time, a certain proportion of microbes is exposed to a high temperature. There has been one publication on this aspect, Poch (M3), who reports that a ten minute exposure to temperatures up to 70°C has no effect on gas production. But above 70°C, the effect quickly becomes predominant; at 100°C, gas production is reduced to 10% of the original.

4.4 Physical form and chemical composition: the cellulose-problem.

4.4.1 The digestibility of ligno-cellulosic materials. Interest in the anaerobic digestion of vegetative material may come from various quarters:

(a) processing fodder for animals, for example, the possibility of preparing birch wood for sheep fodder, the interest being in the digestion in the rumen;

(b) feasibility of industrial fermentations of cellulosic substances for (i) energy recovery, (ii) production of chemicals; in this connection, quite some research has been carried out in Canada and the USSR to find suitable applications for wood waste (cf section 2.4.2);

(c) comparing the effectiveness of aerobic and anaerobic digestion in reducing the solids content in sewage (sludge) and similar wastes;

(d) in connection with the fertilizer value and humic content of manure and its further decomposition in the soil.

The constituents of plant and tree materials are commonly divided into the following groups: lignin, hemicellulose, cellulose, fats and waxes, proteins, ash, and water-soluble constituents. By definition, inorganic compounds cannot be digested (ash and part of soluble constituents). Research on the digestibility of fats and proteins, as they occur in vegetative materials, has not been reported. It may be speculated that proteins will digest quite well, whereas fats will not, but the information on anaerobic digestion is still limited in this respect. Fats are usually low in concentration, except in pine needles.

The discussion on the digestibility of cellulosic materials concentrates on the digestibility of lignin, cellulose, and hemicellulose. The latter consist mainly of pentosans and in some publications, hemicellulose and pentosan are considered synonymous. The chemistry of these compounds will not be reviewed here. It should suffice to note that they are all macromolecules and if present together in one solid phase, quantitative chemical analysis of the different compounds is very difficult. This fact is the major reason why there has been so much confusion in this century over the relative digestibility of the different cellulosic compounds. By now (A17, C9), it is generally accepted that lignin is virtually undegradable, whereas its presence in natural fibres provides both a physical and a chemical barrier to enzymes that can attack (hemi-)cellulose. Physically, penetration by large enzyme molecules is suppressed; chemically, lignin-carbohydrate complexes form metabolic blocks that inhibit polysaccharide hydrolysis. Therefore, in assessing the suitability of various vegetative wastes as substrates for anaerobic digestion, both the lignin content and the physical form (including the effect of pretreatments) is of great importance. Until now, no studies on any scale have been carried out on this subject.

In the 1930s, large research programs on the decomposition of maize stalks and a few other farm wastes were carried out in the United States. Some of these results and a few others on the relative decomposition of lignin, hemicellulose, and cellulose are gathered in Table 4.7. Given the reliability of the analytical techniques then available, to determine the different components, as well as the rather unsystematic way of collecting data, these data are now primarily of historical interest.

4.4.2 The possibility of two maxima in the gas production. As yet, there does not seem to be a clear picture of the relative digestibility of cellulose and hemicellulose. Of course, the way in which the lignin is present, causing more or less obstructions for either of them, may explain this lack of simple conclusions.

There have been occasional reports in the literature that in batch digestion of manure, two maxima in the gas production may occur. The most clear examples of these have been reproduced in Figs. 4.9 and 4.10. Ducellier (F48) has ascribed the first maximum to the decomposition of hemicellulose, and the second to cellulose. These observations seem to have gone unnoticed in the German and English literature. It is difficult to judge whether the two maxima are really related to two more or less independent digestive processes. Cellulolytic bacteria are present in relatively low numbers (A13) and grow or adapt slowly, so that it is possible that their activity will yield a second

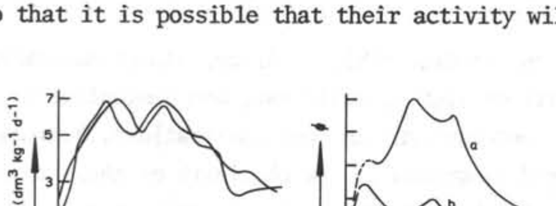


FIG. 4.9 Gas production rate when fermenting 1 kg cow dung at 35°C (Klawenek and Pentkowski, 1962, M64). The two curves are duplicates. The two maxima in the gas production rate were always found when fermenting about 1 kg cow dung or manure, but not when fermenting 1000 kg manure on pilot-plant scale. For manure, the second maximum was observed reproducibly after about 25 days, independent of the suspended solids concentration (7-14%).

FIG. 4.10 The occurrence of two maxima in the gas production rate, the first ascribed to the decomposition of hemicellulose, the second to cellulose: (a) for 8 m^3 manure, measured by Ducellier and Isman in Algeria, as reproduced in (F33) - the dotted line covers the aerobic predigestion; (b), for a large unspecified amount of vine-props (Ducellier, 1959, F48).

TABLE 4.7 Decomposition of cellulosic materials, giving data on the relative decomposition of cellulose, hemicellulose (or pentosans) and lignin, as well as on the effect of pretreatment. The decomposition, β, is given in % weight. (The reliability of these data is disputable.)

substrate and pretreatment	$\alpha(m^3/kg)$	β,total	β,cellulose	β,hemicellulose	β,lignin	t(days)	reference
maize stalks			60	60	30	400	E2
alfalfa			58	54	0	400	E2
manure			69	69	0		F15
rice straw			45	60			E5
chopped corn stalks	0.40		45	59	22	30	L8
corn stalk flour	0.56		94	79	8	30	L8
chopped corn stalks, washed and screened		34	56	55	35	30	L8
shredded maize stalks	0.29					52	L7
as above plus water treatment	0.37					52	L7
as above plus lime treatment	0.57					52	L7

maximum in the gas production rate under batch conditions. It should be noted that the two maxima have only been observed for systems that have passed through an aerobic predigestion (cf also section 4.5.2 on "butyrification"). It is therefore also possible that the first maximum corresponds to the anaerobic digestion of the aerobic bacteria.

4.4.3 The effect of leaching and mechanical pre-treatments. In general, any treatment to depolymerize and solubilize or remove lignin will make the cellulose in lignocellulosics more susceptible to action by enzyme molecules (cellulases). Chemical methods to do this are well-known from the wood pulping industry. Some results are available on alkali treatment (L7), which increases the gas production rate; see Fig. 4.11. However, results are not very consistent. For small-scale application, this does not seem an appropriate option. For large-scale treatment this is different. For example, if it is true that alkali treatment of pine tree needles triples gas production (L7), it is certainly worth investigating this possibility. At present

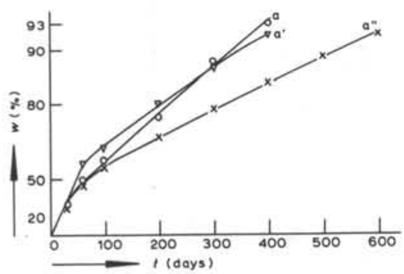


FIG. 4.11 Specific gas production in long time digestions of 15 g corn stalks at 26°C (Buswell, 1939, L7). Experiments were carried out with water-soaked, lime-soaked and untreated samples (a, a', and a" respectively).

such research has only been carried out in connection with the possible anaerobic digestion of refuse. Soaking or boiling in water, moist- and dry heat expansion, can be considered as physical pre-treatments. Data available (L7) suggest that it has little effect.

Microbial and enzymic pre-treatments are sometimes possible; for example, the use of "white rot" fungi to degrade lignin in wood. As far as is known, this possibility has never been considered in the present context.

Mechanical pre-treatment consists of crushing, milling, or any other form of size reduction. The positive effect of this is well-documented. Data for grain straw chopped in different sizes or milled to flour are presented in

Figs. 4.2 and 4.5. The gas production rate strongly increases, although the maximum gas production is virtually the same, which supports the idea that the factor involved is the accessibility of (hemi-)cellulose, not the digestibility of one component or another. A positive effect of crushing elephant grass before starting digestion was reported by Boshoff (P31). It has twice been reported that fragmented rice straw ferments better than powdered rice straw (E5, P25). This is probably due to the fact that the powder forms a compact layer (in the non-stirred digester), which reduces the contact between microbes and substrate.

4.5 Other parameters affecting the biochemistry and microbiology

4.5.1 Nutrients. The microbes active in anaerobic digestion consume carbon and nitrogen in a ratio of 30:1, and further, they need small quantities of phosphorus, calcium, and other trace elements. Most natural organic wastes will contain enough of the trace elements; only nitrogen deficiency may present a problem. (This can be different for the more "pure" industrial wastes.) In Table 4.8, carbon-nitrogen ratios, C/N, are given for a number of animal and plant wastes. Two points should be kept in mind. First, the C/N ratio as measured in the feed, does not need to be equal to the C/N ratio available for microbial consumption (cf. the previous section on lignin). Second, the C/N ratio in a particular type of animal or plant waste is usually not constant (depending on the use of fertilizer, the weather, other vegetation present, etc.).

There has been no systematic research on the effect of the nutrient concentrations on the gas production. The lack of interest in this aspect in Western Europe can probably be explained by the fact that the prime interest was in digesting cow manure, whereas indications of nutrient deficiency have never been observed for these systems. A few studies from India and Egypt of the effect of adding nitrogen, phosphorus, potassium, calcium and magnesium salts when digesting rice straw and/or cow dung have been reported (E5, N6, P25), but they lead to ambiguous conclusions. General opinion in India is that ammonia inhibition has never been a problem.

From the earliest developments in France onwards, there has been an interest in using chemical additives which would stimulate the growth of the anaerobic bacteria. In 1950, which was probably the year when the largest number of digesters were in operation in the Lyon area (see section 3.1), about 400 of them were using "Lovilon" as an additive [a polyhalogeneacetate-glycol] (F25). Additives were also advocated in Germany (see text to Fig. 3.12), and in Italy. No systematic studies are available evaluating the

TABLE 4.8 Typical carbon/nitrogen ratios, C/N of some feeds. These data are only indicative of the differences between different types of substrate. Roughly speaking, if C/N < 10 one may expect inhibition due to high ammonia concentrations, if C/N > 50 the microbes will suffer from nitrogen deficiency.

material	% N (weight)	C/N
animal urine	15 -20	1
blood, slaughterhouse wastes	7 -14	2-4
fish scraps, poultry manure	5 -10	5-8
night soil	6	6-10
grasses and hay	2.4-4	10-20
cotton stalks	1.7	30
cow, buffalo, pig, horse manure	1.4-3	15-40
oat straw, flax waste	1.0-1.2	50-60
maize stalks, seaweed	0.7-2	70-80
wheat and rice straw, bagasse	0.3-0.5	120-150
sawdust	0.1-0.25	200-500

effect of additives on anaerobic digestion.

4.5.2 Volatile fatty acids and pH. The production of methane is brought about via volatile fatty acids (VFA), in particular acetic acid. Because the methane bacteria are more sensitive to all kinds of disturbances, overproduction of VFA may easily upset the microbiological balances. The simplest effect is a drop in pH, which first retards the activity of the methane bacteria, and below pH = 4-5, digestion stops completely ("sour" reactor). However, it has also been argued, in the general literature on anaerobic digestion, that high concentrations of VFA in itself are inhibitory to the methane bacteria. This would explain why strong buffering, or adding caustic soda, or similar, when the pH drops, may be uneffective. It has also been speculated that antagonistic relations between various acid-consuming microbes may cause overproduction of propionic or butyric acid. On the whole, not very much is known for certain, and it may well be that the situation is different for different strains of microbes.

Only two publications are available that report specific studies on the effect of the pH in digesting farm wastes (E5, N6). At sewage plants, "souring" is a recurrent problem. In India, where cow dung digesters have been applied on a large scale, there have been no reports of sour reactors. This suggests that when digesting manure, there is no strong sensitivity to the pH and the extisting literature on the influence of the pH (A13, 16) may not

TABLE 4.9 Products formed by anaerobic fermentation after six months for a number of cellulosic materials (E5). In all cases extra nitrogen has been added to the substrate. Without nitrogen addition the total amount of products is 5-15% lower. The amount of products is given in % weight.

substrate	carbon dioxide	methane	acetic acid	butyric acid
wheat straw	18.6	7.3	4.3	1.6
barley straw	14.1	5.8	7.2	2.5
rice straw	21.5	7.6	1.0	0.3
bracken leaves	10.1	4.2	6.2	2.8
grass (lawn mowings)	19.1	9.8	1.3	4.5
rape seed cake	3.2	2.1	17.6	18.6

be very relevant for manure treatment.

Measurements of the concentration of VFA during anaerobic digestion of farm waste are hardly available. Some data are given in (G15, N39). The only recurrent phenomena seems to be that in the digestion of vegetative materials there is often a large production of VFA, which is not converted into methane within a reasonable period of time. Table 4.9 illustrates this for a number of materials after six months of digestion. Similar results were obtained by Reinhold and Noack (G42). There are no simple explanations for this phenomena and the generality is difficult to judge.

In the French literature, following the work of Ducellier and Isman (F5, F20), there has been an extreme concern with the risk of souring due to the formation of butyric acid. It is butyric acid that is stressed particularly, because it is assumed that the formation of this acid is inimical to the growth of methane producing organisms. It is therefore, that in the French school, predigestion is always advocated, not only to raise the temperature, but in particular so that polysaccharides (sugars, starches) and amides (from the urine), which are most active in VFA production, are decomposed aerobically. Ducellier and Isman also stress that, given this risk of "butyrification", one should be careful with speeding up hydrolysis by external means. For example, cotton (rather pure, strongly polymerized, cellulose) digested well, but when first chemically hydrolysed, souring occurred due to high acetic acid and butyric acid concentrations (F20). This may be compared with the practice of keeping bagasse 1-2 weeks in open air to reduce the sugar content, before it is fed to the anaerobic digester. In the establishment literature on anaerobic digestion, only the disturbing effect of propionic acid has been mentioned.

4.5.3 Inhibitors. In general, everything inhibits if there is too much of it. Apart from the references given on ammonia and VFAs in the previous subsections, there has never been any systematic study of the effect of possible inhibitors on the anaerobic digestion of agricultural wastes. On the basis of the experience with municipal digesters and laboratory studies of model systems, the regularly occurring inhibitors are: ammonia (see section 4.5.1); volatile acids and/or pH (see section 4.5.2); sulfide (no problem if it is consumed by sulfur bacteria or if small concentrations of sulfide precipitating metals are present - erosion of metal parts of the digester will often provide these); heavy metals (copper, mercury, etc. - usually no problem in rural areas); oxygen (because of the interest in methane, there should be no leak in the reactor anyway; the oxygen dissolved in the water is, in general, easily consumed by "guards that try to keep conditions anaerobic"; a number of synthetic organic materials (insecticides, detergents, disinfectants).

The problem of inhibition presents batch operation with an inherent disadvantage. In continuous operation, the chances that inhibitors disappear with the effluent before they can do very serious harm is usually greater.

4.5.4 Mixtures. Given all complicated microbiological balances, it might be speculated, a priori, that a mixture of two substrates may give a better and quicker gas yield than the sum of what the individual substrates would yield. Haphazard empirical confirmations have, in fact, been reported. Perhaps the most conclusive example is in the various reports of increasing gas production and digester load at sewage works when garbage was added to the feed (cf. section 2.2.3). On the other hand, no such effect was observed for mixtures of sewage sludge and manure (G50), but a strong increase has been observed when mixing manure with leaves or hay (A7, H3).

Both in France and Germany, there was at the time, considerable interest in how to choose the excreta-straw ratio (F32, G12,36, 52, H3). These considerations were based on the assumption that straw gives 30-40% more methane, but the concern was not so much choosing the optimum ratio, as calculating the amount of straw needed to obtain a certain amount of gas. Only in 1962 were results reported of experiments in which the amount of extra straw added had been varied from 3-9% (G58). Above 8%, the addition had a negative effect. In the range 3-8%, the gas production per unit of organic mass did not depend on the straw concentration. (See also section 5.4 on the effect of straw addition on the fertilizer value of the spent sludge.)

From India, there are a few publications concerned with the general effect of adding vegetative matter when digesting cow dung (N6,46, 48). On average, this seems to have a positive effect, but no specific conclusions can be drawn for the moment.

If the prime interest is digesting large quantities of vegetative waste, adding cow dung is always reported to be beneficial. But, presumably, this has more to do with the anaerobic microbes that naturally occur in dung and act as inoculum, than with the positive effect the dung itself might have.

4.6 Operation parameters

4.6.1 Loading. The loading of a digester can be expressed in the amount of feed processed per unit of reactor volume per day, η(kg $m^{-3}d^{-1}$), or in the amount of gas produced per unit of reactor volume per day, $\emptyset/V$ ($m^3m^{-3}d^{-1}$). For digesters of agricultural wastes, the order of magnitude of the loading is $\emptyset/V = 1$.

Apart from factors already discussed in sections 4.3-4.5, the loading will depend on (i) the concentration of active microbes in the reactor, (ii) the residence time of the feed in the reactor, (iii) the suspended solids concentration (or the liquid content) of the feed.

Provided that one does not decide to digest solid waste (for example, manure with "natural" moisture content), it appears that the suspended solids concentration usually has an optimal value, independent of the other parameters. This is discussed further in the next subsection and in what follows, it is assumed that the liquid content of the feed is fixed.

In continuous digestion, the substrate content is, in general, directly related to the residence time. Assuming that there is a high concentration of active biomass in the reactor - which will be favourable to apply high loadings-, this will only stay there if it is not washed out. That is to say: given a suspended solids concentration of the feed, there is for every reactor design (all other things being equal) a maximum residue time above which the active biomass will be washed out. With increasing residence time, the specific gas production increases. As can be seen from Fig. 4.12, this relation is such that loadings will be higher at shorter residence times. Hence, if the primary aim is gas production, or synthetic manure production, as distinct from waste treatment, every reactor design should aim at providing the best way of keeping the biomass in the reactor at a high through-put of feed. However, there has been no systematic research on the effect of loading in the area under review. (The actual loadings of existing reactor designs will be discussed in section 6.3.)

In batch operation, the situation is slightly different: A period of preliminary incubation (or lag period) is generally observed in anaerobic digestion and is attributed to the time taken for the development of the

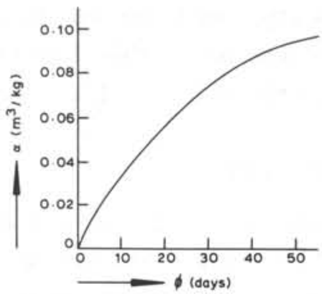
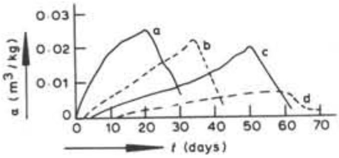


FIG. 4.12 The specific gas production for manure as a function of residence time, based on semi-continuous experiments adding manure daily (Ananiashivili, 1957, M22). Temperature 33°C, solids content 20%. The absolute values of α are probably not very representative (they are very low), but the curve illustrates the general effect of residence time (or loading) on the specific gas production.

specific microflora necessary for effecting decomposition. Therefore, inoculation plays a major role in increasing the (average) loading of a batch digester at a given residence time. The materials most commonly used for inoculation are urine, sludge from a sewage digester, or spent slurry from a previous load. It seems this is also the experience at sewage works, that the amount of inoculant should be quite high to have a significant effect. Typically, in India, it is advocated (N9) that in case of reloading a digester, at least 10% of the volume added should be spent slurry from a good working digester. In France, it was the custom to use urine or drained liquid manure from an active digester to start a new digester. Because sufficient liquid manure is not always available, it has been suggested that 90% of it can be replaced by a 0.2% solution of sodium formiate (F31).

4.6.2 Solids concentration. Already in the 1930s, it had been established that in the digestion of sewage sludge, the optimum solids concentration, C, is 8-10%. Quite some data are available for the digestion of agricultural waste and they seem to support this level of optimum concentration. The major pre-1970 studies on this subject are the following. In Fig. 4.13, results are given, from Germany, for the digestion of horse manure. The specific gas production increases when C is reduced from 25 to 14%. Similar results were obtained in Poland with cow manure at lower values of C (M64). Gas production increases over the range C = 15-8% and seems to be stabilized at about 7-8%. In India, optimal values of 7-9% have been reported for the digestion of cow dung (N9). Below 7%, the "matt" or scum layer builds up strongly. Acharya (E5) found in laboratory studies with rice straw, an



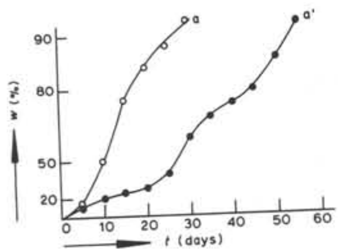


FIG. 4.13 Effect of solids concentration, C, on gas production when digesting horse manure (A7): (a) C = 14%, (b) 17%, (c) 20% and (d) 25% (natural moisture content). In all cases, the digester has been seeded with 10 g "Bacteriozym" per kg dry feed.

FIG. 4.14 Specific gas production of aspen sawdust at (a) 95% relative humidity, and (b) 90% relative humidity (Romashkevich and Kareline, 1961, M30). The experiments were carried out in 0.5 liter flasks, containing 20 g dry material, 200 g fermented deposit for inoculation, and 160 g of tap water. Temperature 32°C. The total gas production at 90% RH is half of that at 95%. Spruce sawdust did not produce significant amounts of gas.

optimum at 10%, and significantly lower gas production at 5%. In Fig. 4.14 data are given from the USSR for digesting sawdust; in which case, it seems that a decrease from 10 to 5% still gives a strong increase in gas production. However, sawdust is not representative of farm wastes in general.

In choosing the solids concentration, apart from its relation to the possible loading of the reactor, at least two other factors may play a role. First, in the arid tropics, the price (or the availability) of water may play a significant role. Unless the reactor design provides good possibilities for recycling the water, this aspect may completely overrule the other considerations. Second, if the digester is to be heated, lower solids concentrations mean more water to be kept at the appropriate temperature.

4.6.3 Mixing. As we have seen in chapter 3, the problem of gas holdup due to the formation of a scum layer is a serious problem. For this reason, the contents of the digester may be mixed, independent of the question as to which way mixing as such may affect gas production. Apart from an Indian study (N37) which concluded that recirculation of the gas doubled the gas production in a 1 m^3 cow dung digester, the effect of mixing in digesting agricultural wastes has not been investigated in a systematic way. A priori reasons that mixing should have a positive effect are: better contact between substrate and active biomass, more effective use of reactor volume (eliminating "dead" regions), less problems with inhibitors (because local overproduction of inhibitors is levelled out). A priori arguments against mixing refer to the fact that the complete digestion process consists of a number of steps involving many different types of microbes. Because the microbes not necessarily all have the same optimal environmental conditions, and some may be antagonistic, some form of stratification, keeping them separate, may be favourable. (Of course products from one step still have to be transported to the next step.) In the case of continuous digesters, an extra aspect is the way mixing affects the washout of active biomass and this may be the major consideration. Of course, mixing is never completely absent, because of the turbulence caused by rising gas bubbles. Under certain conditions, gas bubbles may become very large and will rise through the biomass and "explode" at the surface in a similar way to large bubbles in a boiling liquid or fluidized bed.

5. FERTILIZER VALUE OF SPENT SLUDGE ("BIHUDUNG")

5.1 Summary of major research projects

All in all, not much work has been carried out on the quality of the solid output of an anaerobic digester in terms of fertilizer value. Four institutes have carried out work on a significant scale concerning this important aspect of the evaluation of anaerobic digesters for agricultural waste processing. These four institutes and their interests are as follows:

(a) Indian Agricultural Research Institute (IARI). From 1940 onwards, occasional attention has been given to the fertilizer value of cow dung, comparing anaerobic digestion with other types of manure processing (N2,9,12). Although some information was obtained on differences in detail (see below), no general conclusions were reached.

(b) In the period 1950-1955, research was carried out at the University of Göttingen on various aspects of the output of the "Allerhop" design (see Fig. 3.10) when applied to the field. Nitrogen losses, as well as balances for other elements were studied during anaerobic digestion of manure and various vegetative wastes. Also the extent to which weeds and pathogens were destroyed was studied. In all publications, there is a positive assessment of the "Allerhop" ("bihudung") process (G15,22,23,34). However, the results do not seem to warrant any other conclusions than that the output of the "Allerhop" design is comparable to the outcome of any other good manure processing system.

(c) A large comparative research programme was carried out between 1950 and 1960 at Braunschweig-Völkenrode (cf Table 3.3), in which various designs of anaerobic digesters were studied for their efficiency in preventing nitrogen and other losses, as well as the quality of the manure in field experiments. The main results, together with those from other sources are summarized in Table 5.1.

(d) Some pot and field experiments with manure that had passed an anaerobic digester, were carried out in Poland: "no definite superiority of the manure after methane fermentation over ordinary farm manure could be established in any of the experiments" (M63).

(e) In the USSR, the nitrogen assimilation of fermented sawdust was studied

TABLE 5.1 Summary of main data on the fertilizer value of synthetic manure obtained from various types of anaerobic digesters, compared with traditional methods of manure processing; %N available gives the %(weight) nitrogen in the finished manure relative to the amount contained in fresh manure. Under pot and field experiments, the yield increase is given relative to the yield without using organic manure; the (statistical) error in these data is considerable. %N into plants gives the %(weight) nitrogen taken up by the plant relative to the total amount applied to the soil (= %N available).

description of manure processing operation	C/N	%N available	pot experiments		field experiments	
			%N into plants	yield increase	%N into plants	yield increase
(a) Germany (G43,49)						
without organic manure				100		100
farmyard manure, solids only	16.1		4.5	102	11-14	100-110
farmyard manure, solid/liquid	15.7	83	4/69	102/329	23	110-130
"Allerhop"- Vӧlkenrode	11.7	87	48	275	17	120-140
"Allerhop"- Gӧttingen	9.6	99				
"Darmstadt", solids only	20.1		5.5	86	8.5	105
"Darmstadt", solids/liquid	12.8	48	6/69	86/268	21	105-120
"Lyon", solids only	21.5		4.2	104	19	100-115
"Lyon", solids/liquid	18.0	70	4/40	104/256	38	100-120
(b) Poland (M63)						
farmyard manure		83		110-180		110-125
from large-scale digester (see Fig. 3.20)		97		110-160		110-130
(c) India (N2)						
cow dung farmyard manure	38			130,140		
IARI cow dung digester	25	80(?)		120,190		
(d) Laboratory (M30)						
fermented sawdust (oats)				213		
fermented sawdust (sweet lupin)				107		

(M30). Sawdust is, strictly speaking, not an agricultural waste, so this research will not be further discussed.

5.2 Methodological problems in evaluating organic fertilizers

For various reasons it is extremely difficult to assess the quality of fertilizers from organic sources. Some of the factors on which the quality will depend are:

(a) the form in which the manure is available (liquid content, size of solid particles);

(b) the way it is distributed in the soil;

(c) the carbon-nitrogen ratio, the carbon-phosphorus ratio, the relative proportion of these two ratios, and the presence of minerals;

(d) the properties of the organic material in the manure, in particular, the disposition to mineralize and the amount and type of humic components;

(e) the rain that falls in the period just after the manure has been applied to the soil;

(f) the temperature (in combination with the humidity) that prevails after manure distribution: this strongly affects the microbial activity in the soil.

Even if one would succeed in keeping all these factors under some sort of control, it is still impossible to compare different ways of manure processing. This is the case particularly if the processing time of the systems to be compared is different. Because of the variations in the properties of the excreta of animals, the manure should be obtained from the same animals at the same time. If the processing time is different, it is impossible to take due account of the type of factors mentioned under (a)-(f) above. Together with the statistical fluctuations that are inherent to this type of measurement, it means that only very large and long research projects may lead to any reliable conclusions for the "average" situation.

The carbon-nitrogen ratio (C/N) is commonly used as a general characteristic of the quality of organic manure. Although there is certainly some ground for that, care should be taken with the general application of such a simple parameter. Other things being equal, the same C/N may well have a different physiological effect depending on the way the carbon and the nitrogen are bound. In general, it will be positive if the nitrogen is easily accessible (that is to say, that mineralization proceeds quickly). However, if the manure contains a large quantity of easily decomposable carbon compounds, this may stimulate microbial activity in the soil so much (in particular if it is warm and humid) that no nitrogen is left for the plants, unless the C/N ratio is very low.

Two other important points in connection with the use of the C/N ratio should be noted. First, it makes quite a difference at what point in the manure processing cycle the ratio is determined. Second, in general, the finer the form is in which the manure is applied to the soil, the better the results will be.

5.3 Nitrogen losses

During the early 1950s, when interest in anaerobic digestion in Germany was greatest, it was argued that the loss of cellulose and nitrogen during conventional manure processing was about equal to the amount of these chemicals sold in Germany in 1950. With nitrogen losses during conventional manure processing of 18 per cent or higher, anaerobic processing of manure would seem very attractive, because in principle, nitrogen losses during this process can be zero. Moreover, it may be expected that manure processed anaerobically contains a larger amount of nitrogen that is readily assimilated by plants. Various laboratory experiments support the contention that these advantages hold. However, there is a difference between what is possible in principle and how things turn out in practice.

The major practical problem is that during anaerobic digestion, twenty per cent or more of the organic nitrogen is converted to ammonia (G15,21). Ammonia is readily assimilated by the plants, but is also easily lost to the atmosphere by denitrification. This is illustrated in Fig. 5.1. It follows that the way the manure is handled is of prime importance. This is clearly illustrated in the results of a comparative study with farmyard manure and manure obtained from three different types of anaerobic digesters (G43,49): Only the "Allerhop"-design lives up to expectations; the "Darmstadt"- and "Lyon"- designs give much higher nitrogen losses than during optimal aerobic manure processing (see Table 5.1). The "Allerhop"-design gives no losses because the animal excreta (to which also chopped straw is added) enter at once a completely closed and mechanized system and the synthetic manure only leaves the system just before it is applied to the soil. As has been noted in section 3.2, it is mainly for this reason that the "Allerhop"-system has found wide application, but only in exceptional cases is it equipped with gas collecting facilities.

Another disadvantage might be that in the case of anaerobic digestion, there is either minimal nitrogen fixation from the air, or none.

The risk of nitrogen losses during manure handling has on average been neglected in the discussions about the feasibility of small-scale anaerobic digestion. There are a few references to it in the German literature. In the

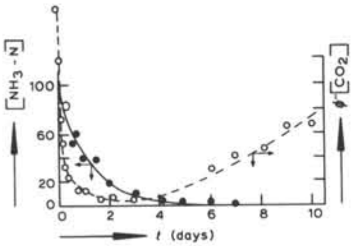


FIG. 5.1 The effect of air exposure on the nitrogen content (as NH_3) of anaerobically fermented cow manure (Kemmler, 1952, G15). Also given is the carbon dioxide "production rate", indicating that after four days, aerobic digestion starts. Although the exact form of the curve will depend on the particular circumstances (size of manure heap, weather conditions), it is clear that the loss of NH_3-nitrogen (which is about 40% of total nitrogen) is so quick that any exposure to air exceeding two or three hours should be prevented.

French literature, this aspect has gone completely unnoticed. There is one Indian publication that deals explicitly with the problem (N9). The advice given is that the cow dung (when taken from the digester) is applied to the soil at once. If this is not possible, it should not be sun-dried (which is common practice), but composted with dry litter or earth. It was not ascertained, however, whether the latter procedure will in fact eliminate "evaporation" of ammonia.

The general conclusion would seem to be, that for small-scale application of anaerobic digestion (in rural areas where the digester should be cheap and simple to operate) there are few possibilities of preventing nitrogen losses, and the alleged better preservation of nitrogen cannot be advanced as an advantage of the anaerobic way of processing manure.

5.4 Other manure characteristics

Kuszelewski and Pentkowski, in Poland (M63), found in comparing anaerobic with aerobic manure processing, that beyond any doubt, anaerobic digestion reduces nitrogen loss and the nitrogen is more easily assimilated. However, both in pot and field experiments with various crops, no difference in yields was found.

Many publications exist containing photographs showing two plots of land, the one treated with anaerobic sludge showing an almost preposterous growth of crops as compared with the plot to which only conventional manure had been applied. Although there may be some bias in these reports, all reports that exist of farmers in France, Italy and in a number of tropical countries are favourable with respect to the manurial qualities of anaerobic sludge.

However, if one evaluates the few more quantitative studies (see Table 5.1), it is doubtful whether any significant differences in crop yields between various manure processing methods have been established. As far as there are any differences, one may expect that they are different for different boundary conditions and different crops, because of the interrelated influence of the presence of nitrogen, phosphorus, and other elements, coming out differently for different crops. For example, in evaluating anaerobic sludge, Sen et al (N12) found little response in rice, but pea yields improved considerably. This may be explained with reference to the amount of available phosphorus in the soil and the extent to which nitrification will occur in the soil.

Apart from the amount and proportion of nutritious elements in manure, its "quality" depends also on the soil stabilizing effect and/or the content of humic substances. Apart from some marginal experiments in Göttingen, no research has been carried out to evaluate these aspects of anaerobic digestion.

Tietjen investigated the effect of temperature and straw content on the nitrogen effect of anaerobically prepared liquid manures. It was found that, with straw contents up to 8%, the physiologically active nitrogen content reduced in proportion to the changing C/N ratio. Above 8% straw, the fertilizer quality became definitely less. Standard cow manure digested at 10°C gave a C/N ratio of 10.1; at 35°C, the C/N ratio was 7.7.

Although few systematic studies have been carried out, it seems an established fact that during anaerobic digestion, more weed seeds are killed than during any other manure processing system. Scheffer et al (G45) reported that 20 to 30 days is enough to destroy the viability of all weed seeds. Most probably it is, in particular, the free ammonia that is formed during anaerobic digestion that poisons the seeds. It was also shown that methane does not kill seeds, but inhibits the germination of them.

In another study, Scheffer and collaborators found no confirmation of the claim that pathogenic typhus-enteritis bacteria are destroyed during fermentation (at 30°C). Although, on average, anaerobic digestion may be considered a more hygienic process than aerobic systems of manure processing, at 30°C only very long digestion time may yield reasonably safe outputs (cf also section 2.3).

6. COMPARISON AND EVALUATION

6.1 Choice of product and production system

Without going into detail, we may state for the present purpose that any production system (hence also an anaerobic digester) can be described in terms of (Q19):

(a) the product or products it should produce (fulfilling some need);

(b) the raw materials; the mechanical, physical and/or (bio-)chemical operations; and the machines and instruments used to process the raw materials into the final product;

(c) the individuals (with their psycho-cultural commitments) and social structures "inside" the production system and the (individuals and) institutions outside the production system that are necessary for production.

(d) the interaction of the production system with the physical and social environment (including macro- and long-term effects).

A production system (to be developed, to be installed, to be subsidized, ...) is appropriate, when the best production system is chosen relative to a given set of "ultimate" value judgments, and put into operation according to expectations - given a correct analysis of the boundary conditions and their possible change. (The value judgments provide the priority assigned to making particular products, and an evaluation of the effect any system may have on its physical and social environment.)

It is beyond the scope of this review to give an evaluatory assessment of (small-scale) anaerobic digesters on this general level. In the case of digesters, the importance of the products (energy and fertilizer) will not normally be disputed. However, there are many ways to fulfill the need for energy and fertilizer. Whether anaerobic digestion - compared to other alternatives - is an interesting possibility will not, as such, be discussed. Also macro- and long-term effects of the introduction of anaerobic digesters will hardly be considered. There have been no publications on these particular aspects in the period under review. In the next three sections, we will review (i) choices in the design of an anaerobic digester, (ii) economic parameters, and (iii) socio-cultural adaptation of digester and environment in tropical rural areas.

TABLE 6.1 Characteristics of the major digester designs that have been proposed for agricultural waste on farms. In many cases the information provided in the literature is by no means complete. The descriptions and data have usually been obtained from the references given in the text of the figures referred to. Data that have been estimated or guessed at by indirect means, or are otherwise considered less reliable, are printed in sloping type. Data for the number of digesters installed are as of 1970. V is the digester volume available for input; C is the solids concentration of the input; Θ is the (average) residence time; $\emptyset/V$ is the gas production per unit of digester volume per day; η is the loading in kg dry mass per unit of digester volume per day (η should be equal to 10 C/Θ for batch digesters; it is given separately, if quoted as such in the literature). Under "miscellaneous", the following abbreviations are used: (a) loading/unloading: C, using cranes; G, gravity (overflow); H, hydraulic (using a pump); M, manual; (b) gas holder: F, fixed (not moving); S, separate; C, combined; (c) aerobic predigestion: +, yes; -, no; (d) nature of feed: D, cow dung; M, manure; V, vegetative; S, others; A, any.

FIG.	name, number installed	V (m^3)	C (% weight)	heating	mixing, scum layer destruction	construction materials	Θ (days)	$\emptyset/V$ ($m^3m^{-3}d^{-1}$)	η ($kg\ m^{-3}d^{-1}$)	miscellaneous (a)	(b)	(c)	(d)
(a) strictly batch													
3.1	Algeria (*200*)	2-10	15-18	cf Fig. 3.4	none	masonry	60	0.4	2-3	M	S	+	M
3.2	Paris (*200*)	6-10	15-18	cf Fig. 3.5	cf Fig. 3.5	reinforced concrete	60	0.4		M	C	+	M
3.3	Lyon (800)	6-25	25-30	aer. predig.	not applicable	metal	60-80	*0.5*		C	S	+	M
3.8	Boufarik (2)	100		none	periodic pressure fluctuation					M	F	+	V
3.14	Hannover (2)	15	6-11	recirc. through heat exchanger		wood	21	0.4-0.8		H	C	-	M
3.17	Brussels (0)	15	25	aer. predig.	recirc. drained liquid	metal + cellular concrete	42			M	S	+	M
3.18	Dublin (1)	2.3	*18*	recirc. through heat exchanger		reinforced concrete	90	0.23		M	S	+	M
3.20	Skierniewicack (4)	3-10	*18*	hot water tubes	manual scum breaker	concrete				M	S	+	M

TABLE 6.1 (cont'd) Characteristics of the major digester designs that have been proposed for agricultural waste on farms.

FIG.	name, number installed	V (m^3)	C (% weight)	heating	miximg scum layer destruction	construction materials	Θ (days)	$\emptyset/V$ ($m^3m^{-3}d^{-1}$)	η (kg $m^{-3}d^{-1}$)	miscellaneous (a)	(b)	(c)	(d)
3.24	Belur Math (*20*)	3	*10*	none	none	bamboo, earth				M	S	-	C
3.34	Fuyang (*48,000*)	10-500	12	none	hand stirrer	masonry		0.21		M	C	-	A
(b) semi-continuous, weekly feed													
3.12	Munich (1)	100	20-25	heated walls	spray of liquid	double metal walls	30			M	S	+	M
3.23	Poona (5)	0.2	*8-12*	none	hand stirrer	oil drums	15			M	S	-	C
(c) semi-continuous, daily feed, one chamber													
3.10	Allerhop (15)	100-1000	15	various	rotating jet	reinforced concrete	20	0.7	1.5-2.5	H	S	-	M
3.16	Berlin (2)	30	*15*	hot water	periodic pressure fluctuation	masonry/ concrete		1		H	F	-	M
3.19	Dresden (3)	30-150	15	various	various	reinforced concrete		0.7-1	2-4.2	H	S	-	M
3.15	Delhi (*50*)	8	10	none	none	unburnt bricks	*50*		1.3	G	C	-	C
(d) semi-continuous, daily feed, two chambers													
3.27	Bombay (5000)	7	7-10	none	none	various	27-42	0.5		G	C	-	C
3.28	Ajitmal (2)	75	8	hot water tubes	mech. agitation					G	C	-	C

TABLE 6.1 (cont'd) Characteristics of the major digester designs that have been proposed for agricultural waste on farms.

FIG.	name, number installed	V (m^3)	C (% weight)	heating	mixing scum layer destruction	construction materials	Θ (days)	$\emptyset/V$ ($m^3 m^{-3} d^{-1}$)	($kg\ m^{-3} d^{-1}$)	miscellaneous (a)	(b)	(c)	(d)
3.31	Transvaal *(0)*	1	*20*	none	none	masonry				G	C	-	M
(e)	*semi-continuous, daily feed, linear displacement*												
3.9	Darmstadt (10)	15-60	15-20	steam injection	mech. agitation	masonry	12-20	0.35		C	S	-	M
3.21	Illinois (3)	5			rotating drum	metal			2-3	M	S	-	C
3.32	Johannesburg (2)	100	20	hot water tubes	mech. "scum drag"		30-60		3.5	M	S	-	M
3.33	Makerere (1)	0.2		none	mech. agitation	oil drums		0.83	2.5	M	S	-	V

6.2 Design parameters

Most of the digester types that have been reviewed in chapter 3 are gathered in Table 6.1, together with their major design and construction characteristics and performance parameters as far as available. The major choices in the design of anaerobic digesters can be summarized as follows.

6.2.1 Reactor type. In general, three fundamentally different reactor types can be distinguished for vessels containing a (more or less) continuous phase: (i) pure batch; (ii) continuous, ideally mixed; (iii) continuous, ideal plug flow (linear displacement). Some of the digester types reviewed here are operated in batch, most semi-continuously, and none really continuously. The class of semi-continuous reactors is very inhomogeneous. The nearest to continuous operation are the reactors with daily loading and unloading. But longer periods between (un)loading are quite common. In addition, the frequency is not always the same for loading and unloading. In this case, unloading is usually less frequent than loading. In some cases, the reactor is operated semi-continuously for some time, then emptied completely.

Similarly, in the class of semi-continuous reactors, the ideal situation of a completely mixed or a plug flow reactor does not occur. Because of gas production, there is always some mixing of the contents. Plug flow may be enhanced in so-called two-chamber digesters. See on mixing further section 6.2.4.

In general a (semi-) continuous reactor works better than a batch digester, although it is more difficult to operate (in particular on a small scale). A major disadvantage of batch digesters is that gas production is irregular and several digesters have to be operated to ensure constant gas production (cf section 3.1). The retention time in a batch digester is usually higher, which results in a larger reactor volume for the same capacity.

If the choice is to digest a non-flowing substrate (cf next subsection) or for applying aerobic predigestion, a batch digester would seem to have inherent advantages, particularly if investment costs have to be minimal. These aspects need therefore, to be considered in combination when comparing reactor types.

6.2.2 Substrate consistency. As can be seen from Table 6.1, anaerobic digesters are operated at various solids concentration, C, of the substrate. Most digesters reviewed here are meant to work on manure. The "natural" solids content of this is in the order of 25-35 per cent (weight). It is quite wet, but not flowing and certainly not pumpable. The effect of the solids concentration on digestion has already been briefly discussed in section 4.6.2. Taking the extremes of a solid pileable manure and an easily pumpable slurry the advantages and disadvantages of the two alternatives can be summarized as follows:

Handling liquids is much easier than solids. Working with liquids becomes more advantageous if labour costs are high (cf section 3.2 on the mechanization of manure processing). A disadvantage of liquid manure can be the formation of a scum layer. Digestion of a solid heap, particularly if it is a few meters deep (which results in considerable compression), may also lead to the formation of a strong film on the surface (made up of emulsion colloids), which prevents easy gas release. However, this is not comparable with the problems caused by scum-layer formation when digesting in the liquid phase. On the basis of the historical review, it may be concluded that scum-layer formation is the major problem of operation. Apart from the digester itself, the scum-layer will also present a problem in the storage vessel for spent slurry (necessitated by the fact that the output of the digester is not normally applied to the soil at once).

Another disadvantage of working with liquid is that the manure has to be thinned with water, with the exception of pig excrement. In some places, this may present a cost in itself. Apart from that, it implies that the same reactor volume contains less solids; hence, loading may be expected to be lower, and hence, investment costs higher. In addition, the extra water also has to be heated (whereas with solid manure, the conductivity is lower, which may reduce heating costs even further). On the other hand, heating of a liquid is simpler, and usually more efficient, than heating a solid (cf section 6.2.6).

Although there seem to be many reasons to consider the digestion of solid manure, few successful applications of this alternative are known. It is difficult to judge whether one has already tried hard enough to exploit the benefits of this alternative.

In most cases, animal excreta is mixed with straw or the input of other vegetative material. The effect of the size of the vegetative waste pieces (unchopped, chopped, short chopped) has already been discussed in section 4.4. Other pretreatments of vegetative waste include: aerobic predigestion, soaking in water, exposure to the sun (in the case of straw and stalks: partly to reduce the sugar content, partly to destroy the waxy coating on the surface).

6.2.3 Separation and processing of spent sludge. Most semi-continuous designs try to approach some form of linear displacement. That is to say, the mass taken out periodically has not the same composition and constituency as the average in the digester. The more important considerations are:

relative position of feed and discharge pipe, geometrical obstructions to prevent back-mixing and short-circuiting, and attempts to take advantage of density differences.

The differences caused by the solids concentration of the digester contents have already been discussed in the previous subsection. In some cases, the output is separated in two parts: solid- and liquid-manure. Nitrogen losses are smallest if the output is stored under anaerobic conditions until applied to the land. However, in practice, all small-scale designs store or stack the output open to the air.

6.2.4 Mixing, and scum-layer destruction. The various ways in which the contents of the digester may be agitated are listed in Table 6.1. The necessity to destroy the scum-layer may well conflict with the wish to approach an ideal plug flow reactor in continuous operation, or to keep some form of stratification intact in a batch or (semi-)continuous reactor. (See on mixing also section 4.6.3.)

The properties of the scum layer depend on the feed. For example, in India, where cow dung which contains very little fat is digested, the scum layer (also called "matt") is quite dry, but still so dense that the passage of gas can be completely blocked. In other cases, the scum layer has more of the properties of jelly.

There have been no systematic studies comparing the different techniques of scum layer destruction (or removal). It has often been overlooked that many organic materials have a density less than 1. Hence, they will float anyway, no matter whether gas bubbles are attached or not.

6.2.5 Processing of gas output. It is not possible to operate a digester without some form of gas storage if the gas is to be used. Even in continuous operation, there will be fluctuations in gas production, whereas consumption of gas will normally be subject to large fluctuations in the course of each day. Three different types of gas holders have been used: fixed gas holder combined with digester (cf Fig. 3.16), moving gas holder combined with digester, separate gas holder. Some comments on the possibility of reducing the investment costs for gas storage (40-70% of total costs) have already been made in section 3.4.2. For small-scale digesters, it is often stressed in the literature (particularly in India) that a separate gas holder is disadvantageous (cf section 3.6 and text to Fig. 3.26). It may therefore be useful to list some advantages of a separate gas holder:

(a) insulation of the digester is easier, and the heat loss to the atmosphere much smaller;

(b) there is less corrosion of the gas holder;

(c) the digester can be placed near the place of manure collection and the gas holder near the place of gas consumption - among other things, this makes it easier to keep a constant gas pressure at the point where the gas is used;

(d) access to the digester is easier (for example, in connection with agitation of the contents, "recirculation" of supernatant liquid or input of non-shredded vegetative material).

Before use, usually water and hydrogen sulphide have to be removed from the gas, and in some cases the calorific value has to be increased by reducing the carbon dioxide content. These aspects are not reviewed here (cf also section 3.6).

6.2.6 Heating arrangements. Roughly speaking, the temperature in the digester depends on three things: (i) the ambient temperature: this variable may be influenced by the position of a digester; inside a building (rarely done), in a wind protected position, partly or completely underground; (ii) the heat loss to the atmosphere, which depends mainly on size and insulation; (iii) provision for extra heat sources.

In the past, digesters in Europe were usually heated, whereas those in tropical countries were not. From the economic analyses made in Germany (G33, M4), it is clear that the heat economy of the digester is the major factor in determining its economic feasibility (see also Fig. 6.2). In subsection 6.2.2, it has already been noted that many more heating methods are available if the digester contents are liquid. The best way of heating seems to be to inject low pressure steam (or hot water) into the digester. (The sterilizing effect of steam injection seems to be small - cf section 4.3.3.)

For application in the tropics it would seem that there is considerable scope for improving the heating of the digesters, using solar systems. A further analysis of this aspect falls outside the period under review.

6.2.7 Construction materials. The factors playing a role in the choice of construction materials are of course very different for Europe and India. For small-scale application in poor rural areas, investment costs have to be minimal, whereas to some extent labour intensity is a less critical factor.

Until very recently, moving gas holders were made of metal sheet, which was a major cost. Both the possibilities of a fixed gas holder and that of using synthetic polymers for the gas holder have hardly been investigated.

Many digesters in practice have cracked or displayed excessive gas leakage due to poor construction materials. Non reinforced concrete cannot be constructed to a large diameter. Use of low-quality cementitious materials, or poor construction in itself, may result in significant gas "absorption" by the walls of the digester. In section 3.6 it was noted that attempts to use bamboo have not been very successful.

6.3 Economic feasibility

An economic evaluation of a production system can be made if the "technology" and the "environment" are specified. In the case of anaerobic digesters, the boundary conditions set by the choice of production system can best be classified under three headings:

(a) design and operation procedures: this includes a variety of aspects that have a bearing on such economic parameters as labour-intensity, cost of construction materials, ease of operation and risk of break-down;

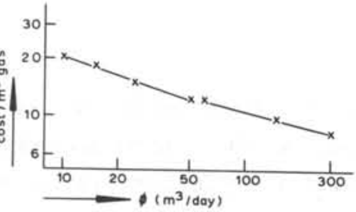
(b) loading of the digester: this is the major factor determining the depreciation of capital costs (as far as loadings of existing designs have been quoted in the literature, they are given in Table 6.1; see on loading also section 4.6.1);

(c) gas production rate: this depends on the many factors discussed in chapter 4; together with the loading, it determines the order of magnitude of the output of fertilizer.

The environment is characterized in economic terms by means of the costs of the so-called production factors (cost of labour, capital, construction materials, know-how, and so on). On the basis of macro-socioeconomic considerations, one may stipulate shadow prices for the production factors. The pros and cons of this way of evaluating are discussed at great length in the general literature. Two examples should suffice to illustrate the type of problems underlying the choice of particular prices of production factors to make an economic evaluation.

First, think of the many statements on un- and underdevelopment in rural tropical countries. On that basis, one might say that labour costs of constructing or operating a digester can be set at zero. However, even if it is true that free labour is available and that other factors (capital costs, cultural constraints) present no problem, it does not follow that the best way to "invest" this free labour is in anaerobic digesters.

Second, take a major part of the digestive system: the gas holder. Assuming that it has to be made from metal, what price should be assigned? In certain parts of France, just after the second World War, there was quite a large amount of waste metal around. Given some ingenuity, appropriate equipment, and free time for a particular individual, the cost of a gas holder may well seem to approach zero. On the other hand, consider plans in India to install hundreds of thousands of digesters. The amount of metal needed for



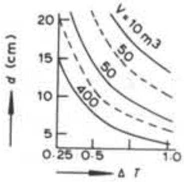


FIG. 6.1 The effect of economies of scale for biogas digesters, as calculated by Feldmann (1954, G21, also in G33) for prices in West Germany in 1953. Data published by Neuling (1956, M6) for the price of gas holders in East-Germany as a function of volume show a similar relationship. These data of Feldmann have also been published, without acknowledgement in Bartha (1958, M42).

FIG. 6.2 The effect of digester volume, V, on the heat loss to the environment (Poch, 1955, M4): d, thickness of insulation layer (conductivity 0.04 J/msK); ΔT, temperature drop in 24 hours. Broken lines for digestion at 50°C; unbroken lines for 30°C.

that may well upset the whole "steel-economy" of the country. Or perhaps even more seriously, the shortage of qualified welders may determine a very high shadow price for the cost of gas holders if digesters have to be installed in large quantities.

Before 1970, no detailed economic evaluations of small-scale digesters in India have been published. In the German and French literature, the period of amortization of digesters has been variously quoted as anywhere between four and twenty years. All estimates in the French literature (for example: F27, H3) are too optimistic, particularly assuming too high a methane yield and making too low an estimate of heating costs. In the German literature, there are also many optimistic statements. The more detailed studies carried out by Feldmann and Stauss (G21,33,41) in the early fifties conclude, very broadly speaking, that small-scale digesters (for 1-15 ha farms) are not feasible. Large-scale digesters as part of mechanized manure processing (such as the "Allerhop"-system, cf Fig. 3.10) would just be economical.

The economic studies carried out in East- and West-Germany show strong economies of scale of anaerobic digestion. This is illustrated in Fig. 6.1 for the investment costs of a digester and in Fig. 6.2 for the heating costs. Although choosing and developing the appropriate designs for small-scale application may reduce economies of scale to some extent, they can never be completely eliminated for physical reasons. In the case of anaerobic digesters, the major physical grounds for economies of scale are, firstly, the volume of construction material needed to achieve a certain strength (the strength of a structure being mainly dependent on surfaces, whereas with increasing scale, surfaces increase less than volumes), secondly, the effect of heat insulation as a function of scale (because temperature loss to the surrounding atmosphere is also a function of outer-surface, and not of volume).

Many of the factors that should be taken into account in a critical economic evaluation are not typical for small-scale digesters, but do play a role with all the potential production systems for rural areas. Examples are: problems arising from an underdeveloped infrastructure (for India see Das (1962, N19), or difficulties in constructing and transporting gas holders, non-availability of gas lamps and stoves, and in general, lack of ready technical know-how in the villages; opportunity costs of input materials and the way they have to be collected; absence of capital in subsistence economies. In the period under review there have been no publications that deal in any detail with these aspects in relation to anaerobic digesters.

6.4 Socio-cultural feasibility

It goes without saying that advocating anaerobic digesters on the farm is not the same in Europe as in India. In Europe socio-cultural factors do not seem to have played a significant role: the question was whether or not anaerobic digestion was an interesting economic option. At the time, it will have been said that farmers never wanted to adopt anything new, even if it were clearly in their own interest; ironically, the European farmers seemed to have been acting in an economically sound way in not adopting the suggestions of the Professors of Agriculture.

There have been occasional suggestions in the German literature, in particular from the side of the sewage works establishment (G4,14), that cooperative digesters would strongly reduce costs. However, for the same sort of reasons that farmers in Pakistan do not like to dry their rice communally, German farmers do not like to process their manure communally, and so, the suggestion was never seriously considered. In the Indian literature, there have also been suggestions that village digesters should work on a cooperative basis. As far as is known, this has never been tried.

As has been noted in section 3.6.5, there have been two Indian publications on the acceptance of digesters by farmers (N17,29). Many of the socio-cultural constraints mentioned there and, in passing in other publications, are not specific to anaerobic digestion, but apply to the introduction of all new techniques.

7 CONCLUSION

Some of the points that emerge from this review can be summarized as follows:

(1) Virtually all organic materials that are available on a farm can be digested (see tables 2.1, 2.2 and 4.1-4.5). In practice, gas yields are in the range of 0.1 to 0.3 m^3 gas per kg dry material, although theoretically they can be much higher.

(2) Many predictions and expectations based on theoretical considerations or experience with sewage sludge digesters are not confirmed for the operation of farm digesters (see chapters 4 and 5). Examples of this are: the effect of pre-treatment of the input, the sensitivity to variation in the pH, the sensitivity to temperature fluctuations, and the quality of the synthetic manure produced.

(3) Most experience with anaerobic digestion is based on the findings of sanitary engineers with sludge digesters. Transfer of technology from sludge digesters to farm digesters is possible only to a limited degree. For example, application of sewage works know-how to bihugas plants in West Germany just after World War II, failed in many respects. It seems that the operation of sludge digesters is in general more sensitive to disturbances, whereas the problems in breaking-up the scum layer are much more serious in the case of bihugas plants.

(4) Many aspects of the design of bihugas plants have not yet been evaluated (see chapter 6). Examples of this are: the choice of reactor type (batch, continuous; mixed, plug-flow), and the moisture content of the feed (in particular the choice between "solid" and liquid substrate). This conclusion applies both for 1970 and 1980. In fact, many of the "options" in the design of a reactor listed in chapter 6, and based on research in the 1950s, are not apparent in recent publications on the subject.

(5) Several sources state that the development of bihugas plants in India was hampered because of low quality appliances, such as burners and gas lights. This does not seem to have been a problem anywhere in Europe, and it may be speculated that this is not an inherent problem, but a techno-

economical problem (which can only be a real problem in terms of cost).

(6) Anaerobic digestion may be applied for three quite different reasons: waste treatment (for example, at a large hog farm), manure processing (for example, the "Allerhop" digesters in West Germany), or energy production (for example, the incentive for research of Buswell in the USA in the 1930s). For small-scale application on the farm, the system should always be evaluated as a bihugas plant, producing both synthetic manure and methane gas.

(7) When evaluating the feasibility of bihugas plants, the socio-economic environment, and in particular, the scale of the plant, has to be taken into account. For example, the "Allerhop" bihugas plants in West Germany as well as the interests in East Germany and the USSR, all relate to capital-intensive bihugas plants for large farms. These designs cannot be directly compared with a digester meant for a farmer with three cows in India. However, the objective is still the same: processing manure and production of fuel. In this sense the large-scale bihugas plant is very different from the anaerobic digester designed for the waste treatment at a large hog farm.

(8) From the historical survey, it is clear that often the developments were not mainly influenced by the intrinsic merits of the process, but by the initiatives of a few individuals, often supported by the perennial hope to get something for nothing. The optimism displayed in many European and Indian publications of the 1950s is very similar in style to the optimism displayed in more recent publications on the virtues of biogas plants.

(9) The most common denominator in the advocacies for anaerobic digesters has been the fuel situation, either on a national level, or on the farm. Both in France and India, the only two countries where large numbers of digesters were installed in the period under review, this was the case. If biogas were available, this would supply a clean source of energy which would benefit in particular the farmer's wife. Developments, both in West Germany and France were influenced by the desire to become self-sufficient in energy. More recently, this argument has also played a role in the policy of the Indian Government with respect to bihugas plants. Detailed evaluations as to whether bihugas plants are the best way to achieve these goals have never been made.

(10) The second incentive for considering anaerobic digesters on the farm, was the fertilizer value of the spent sludge. For the "Allerhop"-design in Germany, the developments in Poland and initially also in India, this was the prime incentive. Although a priori anaerobic digestion would seem to have important advantages, the experimental findings reported in chapter 5

do not give convincing support for such an incentive.

(11) In all countries where large numbers of digesters have been installed (France, India, South Korea), the investment costs have been heavily subsidized. This seems to be sensible only if in the long run, one expects a bihugas plant to be economical (at whatever shadow prices one wishes to choose).

(12) If animals are kept in stables, relatively easy and quick transfer of the manure to the anaerobic digester is possible. If that is not the case the costs of bringing the feed to the digester may well be prohibitive.

(13) Designs have to be evaluated relative to local factor prices. Developments in Germany were mainly aimed at reducing labour costs during the manure processing cycle. French and Indian designs were very labour intensive. In India, there have been many unsuccessful attempts at making the system cheaper (use of bamboo and putty; waste tin burners). It is extremely doubtful that bihugas plants are appropriate for the poorest farmers.

(14) Introduction of "new" things in a given society is never easy. This problem is the same for introducing bihugas plants in rural areas in developing countries as for introducing other new techniques. It would seem, however, that compared to other techniques, bihugas plants are very sophisticated items, which ask for a lot of attention, where there are often large "dead times" between "cause" and "effect".

(15) From this review, it is very clear that R & D in bihugas plants has not been very international. The developments in the USA, France, Germany, and India took place almost entirely independently of one another. The language barrier will be part of the problem. It would seem that in the case of bihugas plants, very much can be learned from the experience of the past, or from other places.

(16) Systematic comparison of different designs of bihugas plants was carried out for some time in the 1950s in West Germany at Völkenrode (see section 3.2). In the 1970s, some comparative work with hog wastes was carried out in The Philippines (Q23). No other projects like this have been reported. Given the very large variety of designs that have been proposed and partially carried out, it would seem that there is scope for much more comparative research.

(17) In general, it may be argued that anaerobic digestion and bihugas plants are perhaps an area worthwhile for more large-scale and fundamental research. (Here "large-scale" refers to the size of any particular project.)

(18) From the fact that anaerobic digesters were not successful in Europe after World War II, it does not follow that bihugas plants might not be feasible for developing countries today. However, given the massive

interest in anaerobic digesters that developed in the late 1970s, it would seem that there is something wrong with the way in which the intelligence of the technique has been applied, if so little is known about how to evaluate the appropriateness of different designs, about the experience that was collected at various places in the past, and about the actual performance of digesters in operation.

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This bibliography consists of three parts:

(1) The first part (sections A-E) is thematic and gives selected references to applications of anaerobic digestion, other than biogas and fertilizer production on the farm. These other applications are reviewed in chapter 2.

(2) The second part (sections F-P) constitutes the bulk of the bibliography, and contains the pre-1970 publications on bihugas plants (on which chapters 3-6 are based). This part is ordered geographically, and then chronologically within each geographic category.

(3) The third part (sections Q and R) gives a representative selection of post-1970 publications on small-scale bihugas plants.

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